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## MAGNETIC EFFECTS RESULTING FROM THE JOHNSTON ISLAND HIGH ALTITUDE NUCLEAR EXPLOSIONS

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### *Abstract*

The unusual magnetic effects recorded at five Pacific Island observatories following the explosion of two nuclear devices in the upper atmosphere above Johnston Island are described. The effects have been divided into four phases, each produced in a different way. The initial phase is thought to have been due to a hydromagnetic impulse propagated preferentially along the line of force through Johnston Island and the conjugate point. The second phase is identified with high speed electrons which travelled along the line of force to the conjugate point, where they also produced the aurorae. The main phase and the final phase are believed to have been caused by the expanding conducting cloud produced by each explosion. The respective electric current systems producing the latter magnetic effects arose from motion of the cloud in the earth's magnetic field, their differences being due to the changing geometry of the cloud relative to the regions of maximum ionisation.

### INTRODUCTION

On 1 and 12 August 1958, nuclear devices were exploded in the upper atmosphere above Johnston Island in the North Pacific. No exact information is available to us regarding the heights of the explosions but it is believed that the first explosion was higher than the second. The auroral manifestations seen at Apia after the first explosion have been described by Cullington (1958), and certain deductions made from the phenomena (Elliot and Quenby, 1959; Fowler and Waddington, 1958; and Kellogg, Ney, and Winckler, 1959). The second explosion produced a similar auroral display at Apia (J. G. Keys, pers. comm.) but cloud prevented much detail from being seen. This paper, a summary of which has already appeared (Lawrie, Gerard, and Gill, 1959), will be concerned with the unusual magnetic effects, briefly mentioned by Cullington (op. cit.), recorded after both explosions on magnetographs at Honolulu, Palmyra Island, Fanning Island, Jarvis Island, and at Apia. Fig. 1 shows the location of these observatories.

Vector diagrams showing the departures which occurred in the horizontal plane and in the vertical plane perpendicular to the magnetic meridian are given in Figs 2-6 for the first explosion and in Figs 7-10

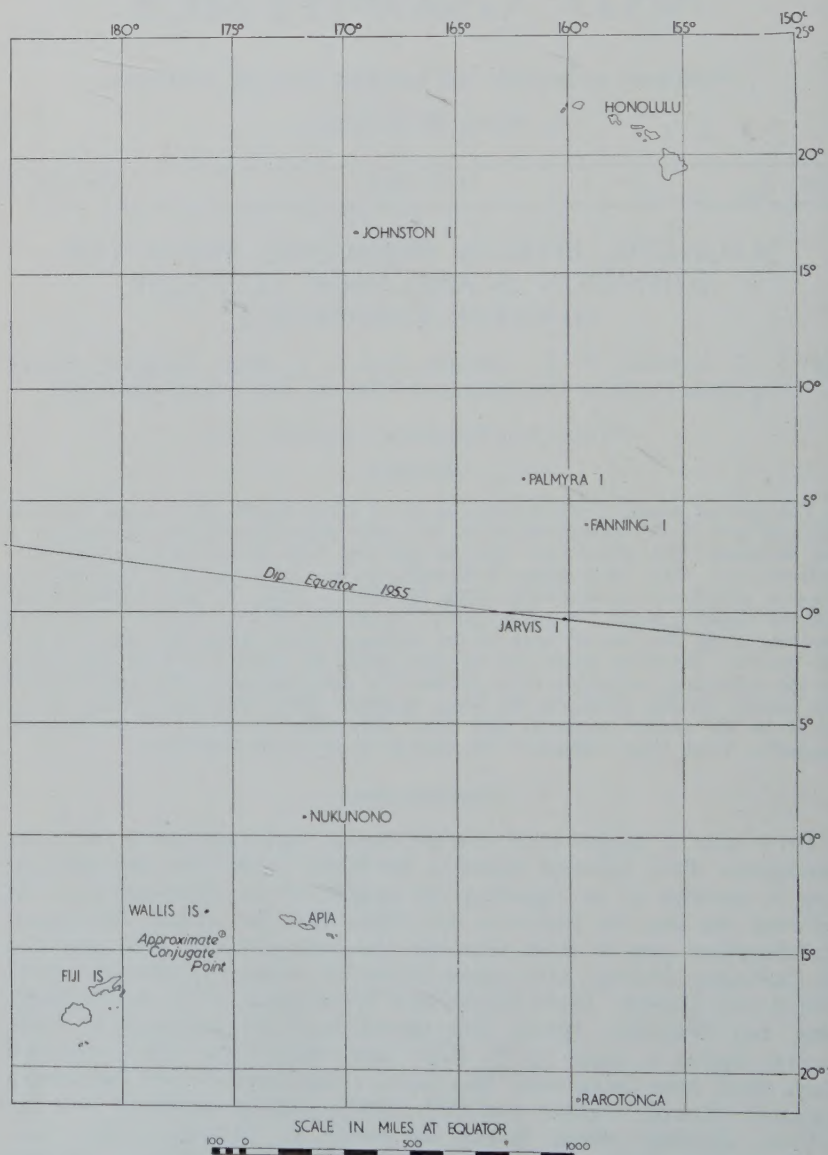
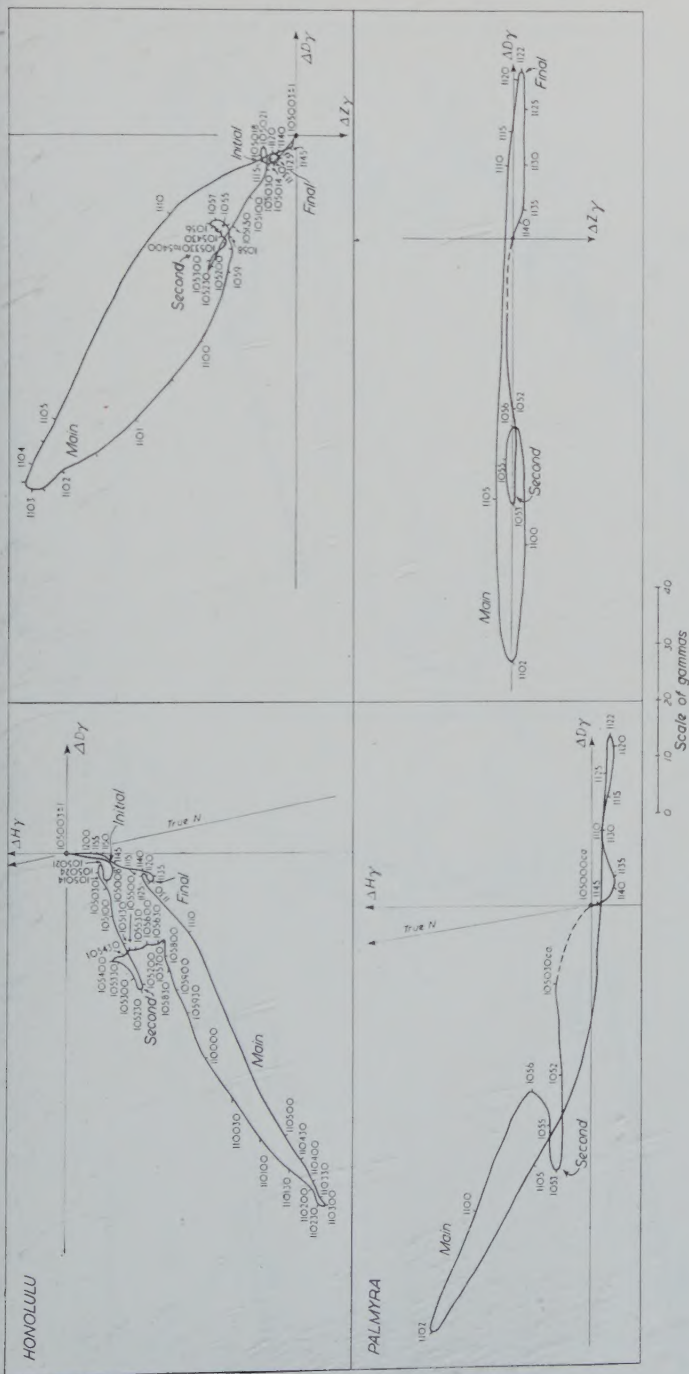


FIG. 1—The region of the Pacific showing islands where unusual magnetic effects were recorded



FIGS. 2-6—Vector diagrams showing the magnetic departures following the explosion of 1 August 1958.

(a) Vector diagrams in the horizontal plane.

(b) Vector diagrams in the vertical plane perpendicular to the magnetic meridian.

FIG. 2—Honolulu. FIG. 3—Palmyra Island.

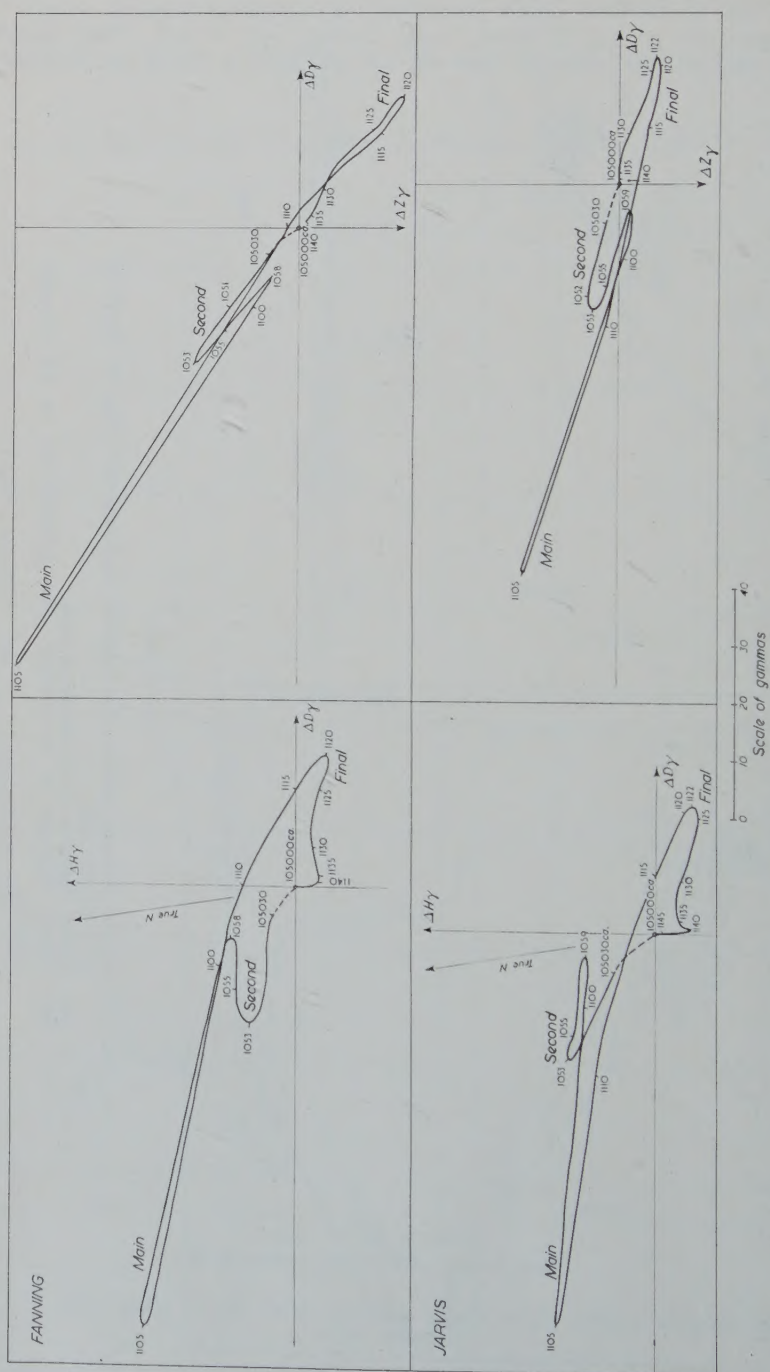
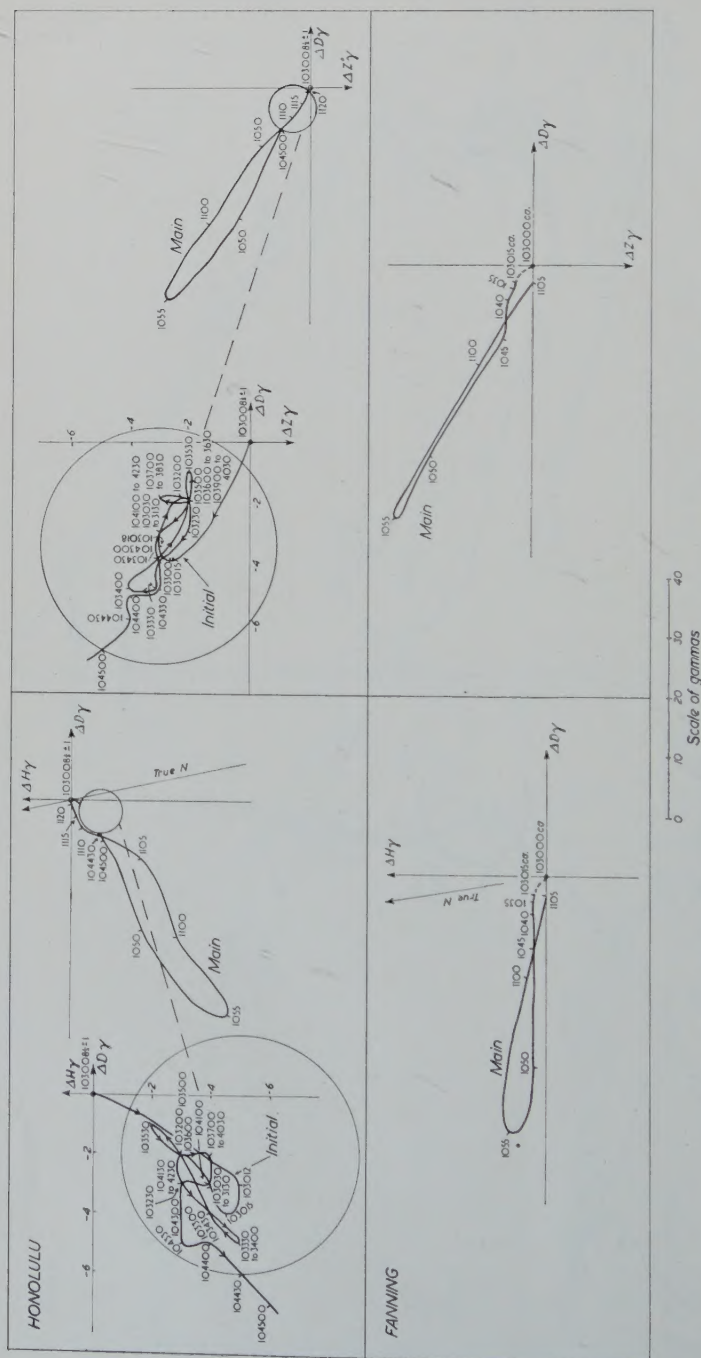


FIG. 4—Fanning Island.

FIG. 5—Jarvis Island.





Figs. 7-10—Vector diagrams showing the magnetic departures following the explosion of 12 August 1958.

(a) Vector diagrams in the horizontal plane.

(b) Vector diagrams in the vertical plane perpendicular to the magnetic meridian.

Fig. 7—Honolulu.

Fig. 8—Fanning Island.

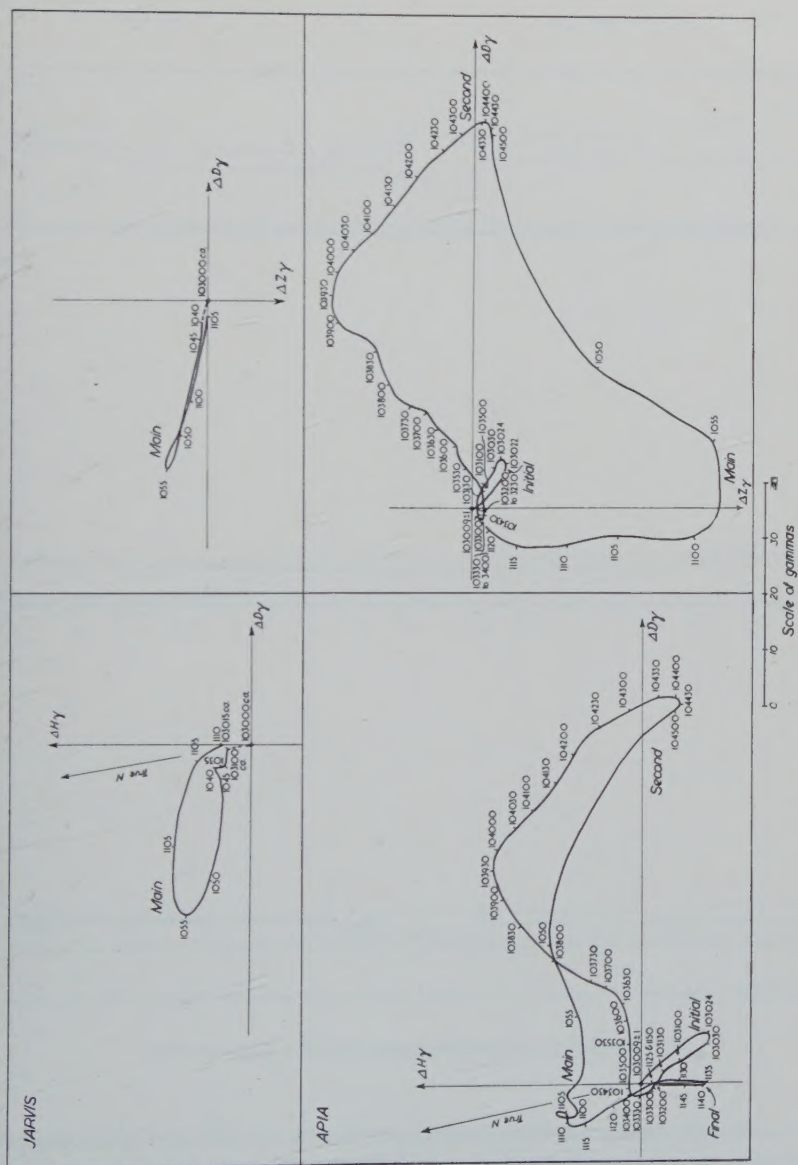


Fig. 10—Apia.

Fig. 9—Jarvis Island.

for the second. There was no record at Palmyra during the second explosion. The Apia magnetograms for 1 August 1958 and 12 August 1958 are given in Figs. 11 and 12 respectively.

To determine the departures, natural background curves were assumed in each case. The shape of the bay disturbance at the time of the first

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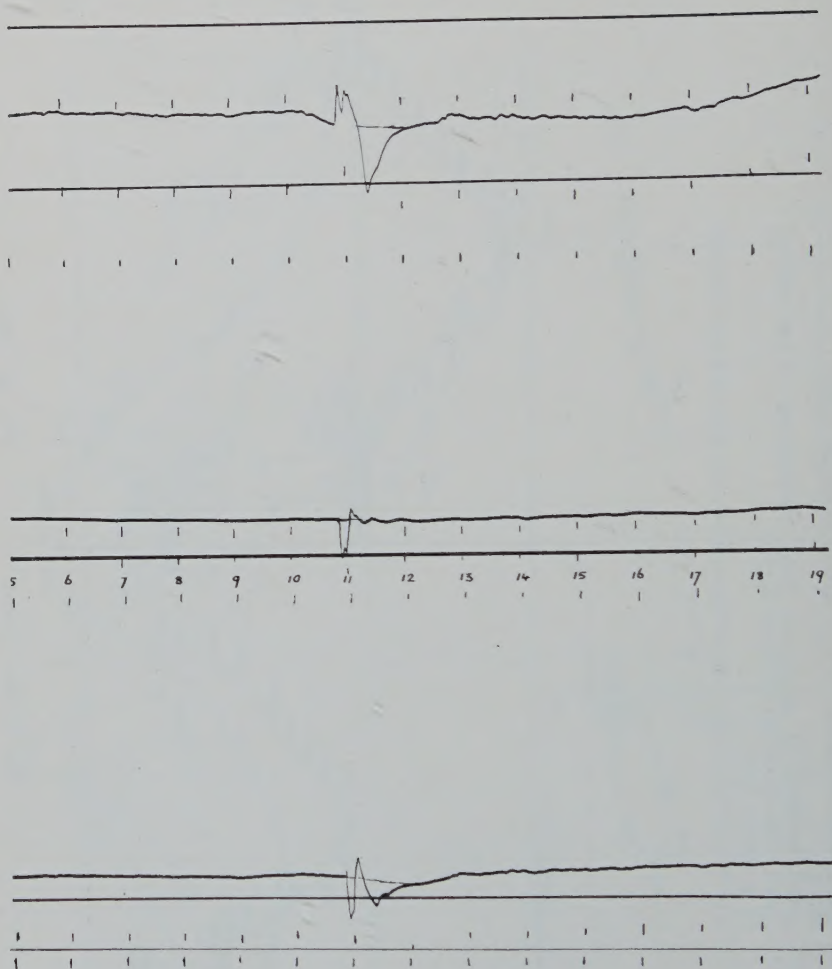


FIG. 11—Apia La Cour magnetogram for 1 August 1958.

explosion was estimated from inspection of the records at Guam, Koror, Amberley, and Sitka. The differences between the recorded and estimated curves gave the departures.

The patterns of disturbance for each explosion are complex and lead to a fairly obvious classification into four phases — initial, second, main, and final, as labelled in Figs. 2–10. The differences between these imply that the magnetic field variations at distant points must have been produced by different mechanisms. Again, though corresponding phases for the two

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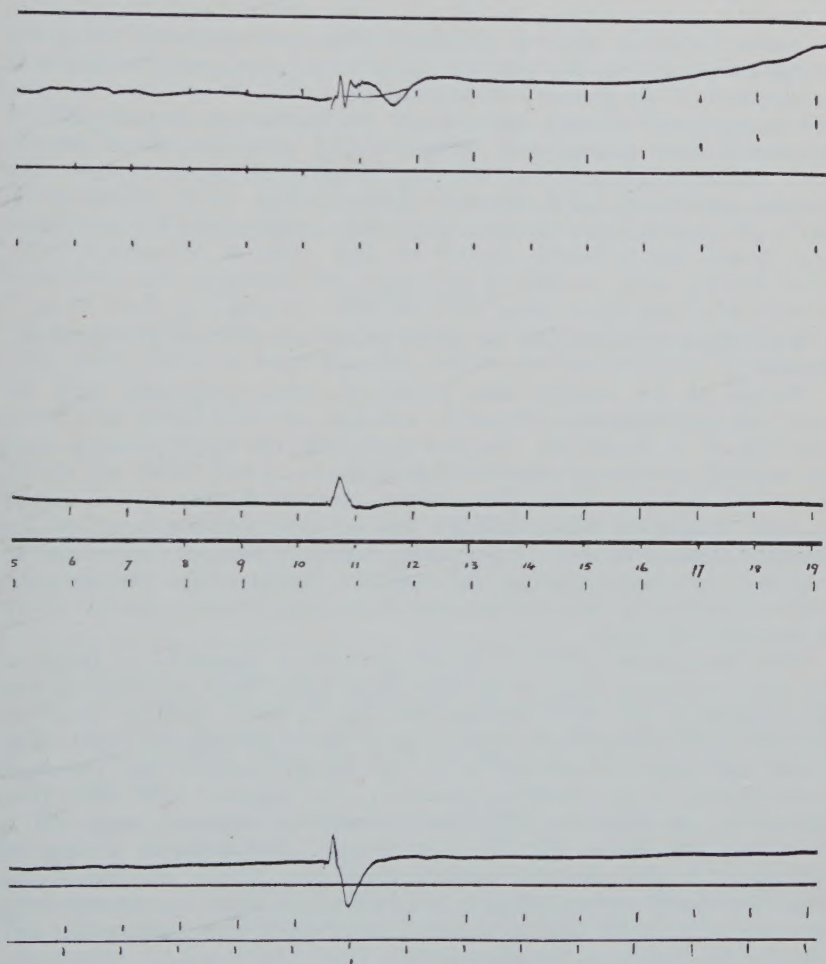


FIG. 12—Apia La Cour magnetogram for 12 August 1958.

explosions have points of difference, particularly the second phases, yet the general similarities lead us to assume the same kind of mechanism for each phase after both explosions.

Now the apparent simultaneity of each phase at all stations raises ambiguity in the interpretation. It is a coincidence that the particular set of stations lies roughly on an ellipse with major axis along the meridian through Johnston Island, and it is therefore difficult to distinguish between travelling and overall simultaneous effects. There are details about the

phases which indicate sometimes one type of effect and sometimes the other. For the main phase in particular there are points in favour of both.

Here we treat each phase on its own merits. For the main phase, which we regard as the key effect, it will be seen that our interpretation is basically of the travelling type, the apparent indication of simultaneity being due to developments in the geometry of the pattern.

Vacquer (pers. comm.) has pointed out that at the three equational stations, induced underground currents during rapid fluctuations strongly affect the vertical component, resulting in systematic ratios  $\Delta Z/\Delta H$ . The marked linearity of our  $Z$  versus  $D$  diagrams, Figs. 2-10, (b), is clearly due to this and we have therefore given little weight to the  $Z$  variations.

#### INITIAL PHASE

It is suggested below that the initial phase was due to a hydromagnetic impulse.

Because of the rapidity with which this phase progressed, only the rapid rate magnetograms at Honolulu and Apia provided useful information (see Figs. 2, 6, 7, and 10). For both explosions, the initial phases at these two stations commenced sharply within a second of each other, and during the second explosion, Keys (pers. comm.) observed that the auroral display at Apia commenced with a brilliant flash of light within a second of the magnetic commencement. This striking similarity between beginnings of magnetic and visual effects at such different distances from the explosion point indicates that the commencement times were within a second or two of the explosion times.

Now the impulse took 4-5 seconds to reach its maximum at Honolulu for both explosions, and 15-20 seconds at Apia. These intervals of time are roughly in the same ratio as the distances from Johnston Island to the respective observatories, which suggests that a propagation speed determined the times of maxima. It is not usually assumed that transverse hydromagnetic waves travelling parallel to the magnetic field suffer from dispersion; but Akasofu (1956) has deduced the dispersion equation for ionospheric conditions, and charts the speed  $v$  frequency for a range of ionosphere heights, showing definite dispersion. In fact the speed read from this chart, corresponding to a frequency of about 1 cycle/sec, is of the same order as the theoretical speed which would correspond to the incidence of the maxima of the initial phase.

We therefore postulate that the initial phase was a transverse hydromagnetic impulse suffering dispersion, originating with a very steep front which became increasingly spread out in propagation.

Dispersion of transverse waves travelling perpendicular to the magnetic field has not been so fully treated, no doubt because of greater mathematical difficulty; but because of the relationship found above between the times at Apia and Honolulu, the latter being on a line at  $56^\circ$  to the meridian through Johnston Island, we further postulate that the speed of propagation of the impulse was of the same order in all directions.

The amplitude for both explosions was about twice as large as Apia as at Honolulu; thus the impulse certainly suffered much more damping perpendicular to the magnetic field than parallel to it.

Kellogg *et al.* (1959) point out that the great increase in the conductivity along the line of force through Johnston Island, produced by the fast travelling electrons, must have complicated hydromagnetic propagation along the same path; but in the beginning the tube of force traversed by the electrons was only a narrow one and the path of the hydromagnetic impulse travelling to Apia would be outside it.

The electrons, escaping from the growing hole in the magnetic field created by the explosion, may have been able to carry some "frozen in" field with them, perhaps coupled with the hydromagnetic impulse.

Matsushita (pers. comm.) opines that the initial phase was produced largely by charge separation. The objection to this explanation is that if the drift velocity had an effect, then the velocity parallel to the lines of force must have had a greater one. Assuming an electron speed parallel to the lines of force of  $10^{10}$  m/sec. then the drift speed would be of the order of  $10^{-1}$  m/sec. With such a large numerical factor involved, it would take a very potent factor to make the drift velocity the more effective of the two.

## SECOND PHASE

The departures for this phase have their greatest amplitudes at Apia, and are there more important than the main phase effects. They must therefore have resulted from a transport of material confined to the magnetic lines of force.

There are two possible ways that this could have occurred:

- (1) Escape of individual charged particles;
- (2) More rapid motion of the shock wave parallel to the magnetic lines of force than across them, in a region of low atmospheric pressure where motion across the magnetic field is resisted through induced currents.

We reject the latter possibility during the second phase, because the subsequent magnetic fluctuations at Apia did not include those which we would certainly expect under these circumstances, resulting from eventual development of a radial wind about the conjugate point. We thus conclude that individual charged particles escaping to the conjugate points were responsible for the second phase effects at Apia.

In addition to the  $\beta$ -decay electrons considered by Fowler and Waddington (1958)  $\gamma$  rays from an explosion would produce electrons outside the fireball by pair-production, Compton and photo-electric effects, and these would add to the overall effect.

Subsequently, the fireball would expand upwards in the direction of decreasing atmospheric pressure, and as it did so, particles of lower and lower energies should be able to make their escape. Eventually, positive ions might emerge.

Now the auroral displays evidently revealed the actual arrival of particles, and yet there was a definite difference between the morphologies of the auroral displays and of the second phase effects. In general, the auroral displays commenced sharply and gradually diminished, whereas the second

phase effects grew more slowly reaching their maxima later. This can be explained in two ways:

- (1) The second phase effects could have been due to electrons of less energy than those producing aurorae;
- (2) The magnetic effects could depend on the total number of electrons which had arrived by a given time, therefore having a form related to the time integral of the auroral effect.

It is difficult to decide between these two and perhaps both contributed.

Another feature is the substantial amplitude of the departures at the equatorial stations for the first explosion, shown in Figs. 3, 4, and 5. These are larger than would be expected to have resulted from electron or ion motion strictly confined to the line of force through Johnston Island. We suggest therefore that large numbers of high energy neutrons escaped from the fireball, and by subsequent radioactive decay, broadened the region over which the charged particle motion occurred.

In general, the second explosion, being at lower altitude, probably produced the ionisation effects over a narrower region and also developed more slowly.

We discuss below one or two possible mechanisms for the production of the actual magnetic effects.

The second phase effects of the two explosions were quite different. That following the first one appeared to begin more or less at the time of the explosion but was at first obscured by the initial phase. It was recorded clearly at all stations, with very large amplitude at Apia, and reached its maximum in about 3 minutes everywhere. However, after the second explosion, this phase appeared only at Apia, where the vector was still large but oppositely directed from that of the first explosion and its maximum occurred after about 14 minutes.

The most direct interpretation of the effect at 1053 GMT of Figs. 3-6 is of an electron stream flowing from north to south. However, the opposite direction of the vector at Apia after the second explosion (Fig. 10) can hardly be explained this way, so that while the direct magnetic fields of the flowing charges probably did contribute, other types of effect as well must have been important.

The direction of the vector at Apia for the first explosion is roughly consistent with a dynamo current due to locally increased ionisation in the Sq wind system (Chapman and Bartels, 1940). The oppositely directed vector recorded at Apia after the second explosion indicates that the wind responsible would have been in the opposite direction. This could have resulted from the difference in the natural magnetic conditions on the two occasions, or because the effective ionisation was concentrated at different levels, where differing wind systems were predominant.

#### THE MAIN AND FINAL PHASES

The important facts about the main phase are:

- (1) The amplitudes of the departures are of the same order at all stations.

- (2) While the effects were broadly simultaneous, the times at Honolulu, Palmyra, Fanning and Jarvis following the first explosion (Figs. 2, 3, 4, and 5) suggest an effect spreading from the region of Johnston Island.
- (3) The main phase of the first explosion was very similar to that of the second but larger and sooner.

The equal distribution of amplitudes, in contrast with the strongly anisotropic distribution in the second phase, shows that the mechanism working at this time was much less controlled by the magnetic field, and more active in the region surrounding Johnston Island.

In fact the most natural interpretation of the magnetic vectors is in terms of an expansion of conducting gas from Johnston Island. Currents would have arisen from motion relative to the earth's magnetic field, and also by induction in order to keep lines of force to some extent frozen in the medium.

Matsushita (pers. comm.) has given an interpretation depending on such motion, relative to the vertical field alone, but assuming that it was limited in extent. Because of the earth current effects, the directions of the magnetic vectors do not give any information on this extent. However, as stated above, the times of maximum at the four stations nearest Johnston Island suggest that the effect was a spreading one and that the maximum at each station represented the arrival of some portion of it, if not at the station itself, then at least at some point along the same meridian. Cummack and King (1959) independently propose a shock front which moved with radially uniform horizontal speed from a point near Johnston Island, and they associate the actual passage of the front at a station with the time of maximum of the main phase there; except at Apia, where they associate it with the time of maximum of the final phase.

Hence, adopting the idea of an expanding conducting cloud with circular horizontal boundary centred on Johnston Island, we describe below a mechanism for the production of a current system which roughly corresponds to the magnetic vectors.

This is pictured in Fig. 13 and is built up as follows:

In Fig. 13A can be seen the type of distortion of the horizontal magnetic field which would tend to be produced by a highly conducting expanding gas in order to keep the lines of force relatively fixed in the gas.

In Fig. 13B is pictured a current system which could have resulted from the expansion of the Northern portion of the front against the earth's vertical magnetic field. We assume that conductivity is in general much greater along the lines of force than perpendicular to them. In the Northern section of the ring the e.m.f. would have been strong enough to produce the current pictured. Perhaps the electrons would first be driven to the base of the cloud by the Hall effect, and at this level current would have then flowed. Over the Southern portion  $Z$  is small, and the current would be flowing to constitute a return path. Across the equator this would more easily flow along the meridian and the circuit would close about the latitude of the conjugate point where ionisation had been previously increased during the second phase.

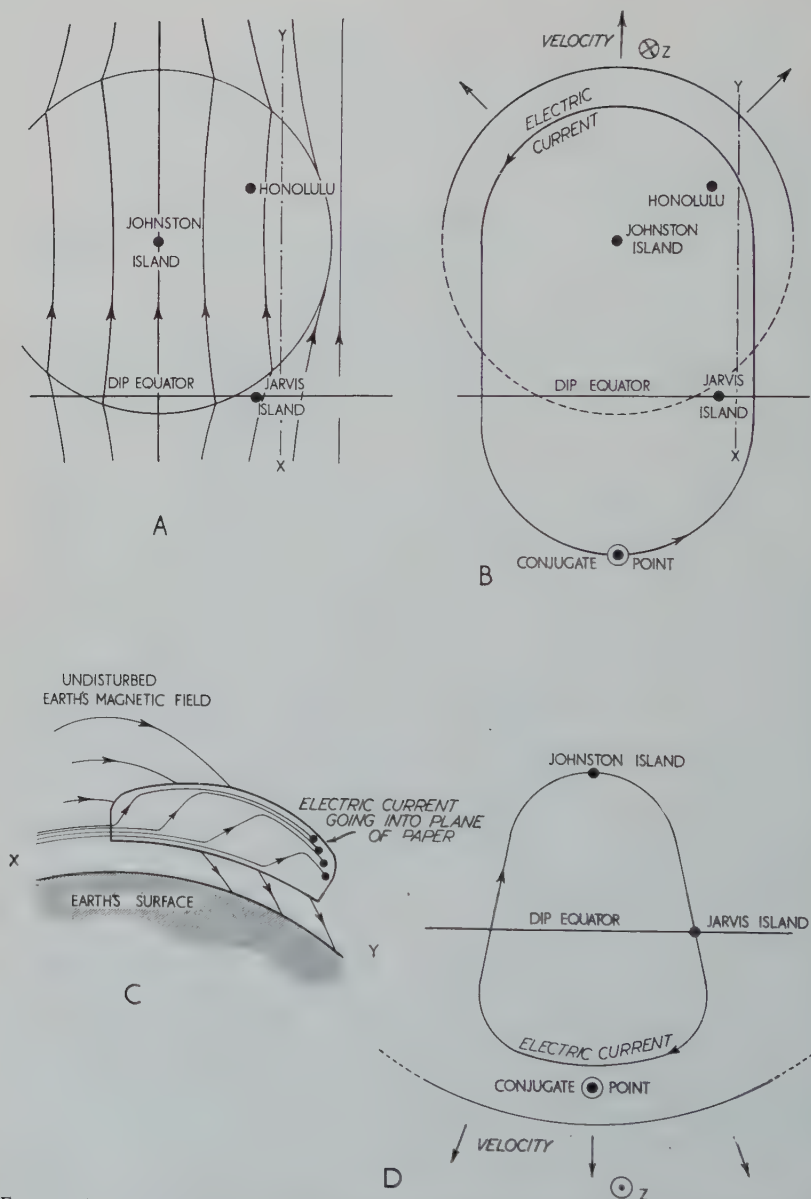


FIG. 13 (A)—Distortion of the earth's horizontal magnetic field during the main phase.  
 (B) Electric current induced by motion against Z of the Northern section of the expanding cloud during the main phase.  
 (C) Current system in the vertical plane across the section X-Y to approximate the distortion in (A), combined with the current system of (B).  
 (D) Electric current induced by motion against Z of the Southern section of the expanding cloud during the final phase.

In Fig. 13C is shown a vertical section across X-Y of Figs. 13A and 13B. In this a current system is shown which combines that of Fig. 13B with currents to approximate the distortion shown in Fig. 13A. It can be seen that the South to North return currents, if flowing near the base of the cloud, would also have contributed to the type of field distortion required by Fig. 13A.

The model pictured does not specify exactly the position of the strongest electric current. We believe that the effect at a particular station would have been a function of time and the geometry of the current system as well as proximity to the motion front, and that the time of maximum would differ from the time of the passage of the front probably by a minute or two.

Fig. 13D gives a picture of the possible situation at the time of the final phase. This is almost symmetrically opposite to the system in Fig. 13B apart from the fact that most of the front had by then passed into a region of lower ionisation. We postulate that the effective part of the e.m.f. at this time would have been in that portion of the front passing through the zone of higher ionisation near the conjugate point. The return current similar to that of the main phase current system, is shown to close in the region of high residual ionisation near Johnston Island. In the second explosion, much recombination had taken place by the time the front had reached the conjugate point, and the effect was therefore much smaller. As no effect was observable at Jarvis Island or Fanning Island for the second explosion (Figs. 8 and 9) then the return current system for this would have been less extensive and may not have extended as far north as Johnston Island.

This interpretation departs somewhat from that of Cummack and King (*op. cit.*) who consider that the effective ionisation was produced by the front, this being in the nature of a shock front.

### CONCLUSIONS

It is proposed that the magnetic effects for each explosion are divisible into four successive phases, each produced differently and that every phase appeared sooner after the first explosion because of the higher altitude. Interpretations of each phase are as follows:

- (1) The initial phase was a hydromagnetic impulse which became less and less impulsive in transit due to dispersion;
- (2) The second phase was produced by individual charged particles pouring along the line of force from Johnston Island to the conjugate point;
- (3) The main and final phases were two successive aspects of the effects of a radial gas motion originating at Johnston Island, and eventually passing over all the magnetic stations concerned.

### ACKNOWLEDGMENTS

The ideas proposed in this paper have all arisen from discussions amongst the staffs of Magnet Survey and Geophysical Observatory, Christchurch. The authors are particularly grateful to Messrs C. H. Cummack and G. A. M. King, for illuminating discussions.

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## A THERMAL PROFILE AND SEA SURFACE OBSERVATIONS ACROSS THE SOUTHERN TASMAN SEA

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### Summary

A thermal profile of the upper layers of the southern Tasman Sea with associated surface and bathymetric observations is presented. Analysis of the data is made for currents and water mass properties. The character of the Subtropical Convergence here is pointed out and longitudinal limits indicated for the various structures discussed. The subtropical, East Australian Current is found to dominate the circulation of the western, southern Tasman Sea while subantarctic water is predominant in the eastern half.

### INTRODUCTION

The observations presented here were obtained by the writer in February 1959 while serving on board USS *Staten Island* (AGB-5) as oceanographer for the U.S. Navy Hydrographic Office during Operation Deep Freeze IV. They consist of 60 surface temperatures, 47 bathythermograph lowerings to an average depth of 700 ft across the Tasman Sea from Banks Strait to Foveaux Strait with concurrent bottom soundings and 16 surface salinity determinations.

The ship's track and locations of the salinity samples are indicated in Fig. 1. Shown also, is a line of surface observations taken south of Australia

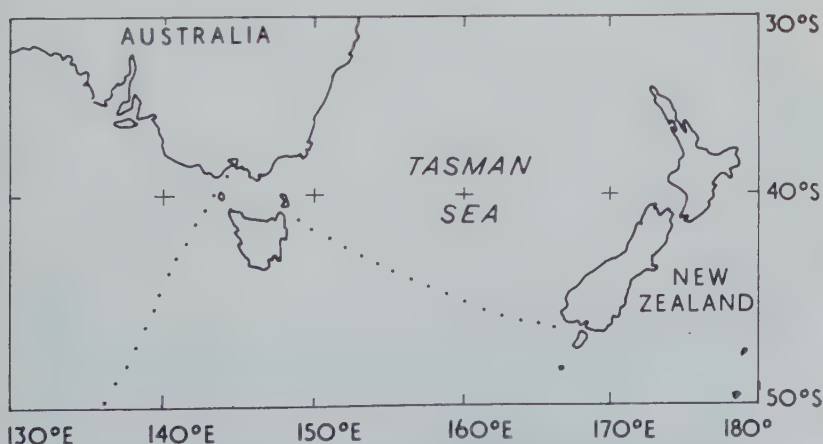


FIG. 1—Track and surface salinity positions of USS *Staten Island* (AGB-5) during February 1959.

a few days before the section. These are used to aid the interpretation of the current structure. The surface data are presented in Table 1. The thermal section, surface plots, and bathymetry are shown in Fig. 2. The dashed portion of the section indicates structure inferred from surface values and the observed part of the section while the winch was inoperative due to

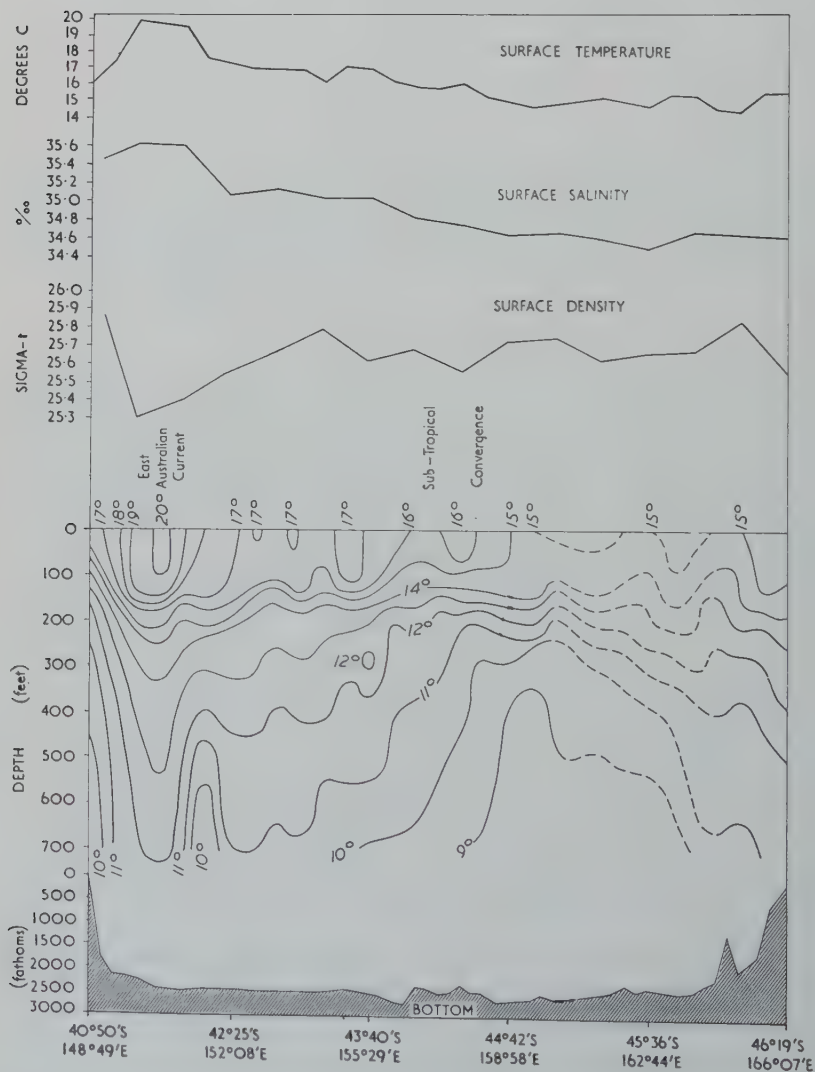


FIG. 2.—A plot of surface values, temperature cross-section, and bottom topography across the southern Tasman Sea, February 1959.

electrical failure. The currents interpreted from the available data are indicated in Fig. 3. A temperature-salinity (T-S) plot indicating the inferred water masses and their movements is presented as Fig. 4.

TABLE 1—Surface Data Summary: 11–17 February 1959

| Latitude<br>°(S), | Longitude<br>°(E), | Temp.<br>°C | Salinity<br>0/00 | Latitude<br>°(S), | Longitude<br>°(E), | Temp.<br>°C | Salinity<br>0/00 |
|-------------------|--------------------|-------------|------------------|-------------------|--------------------|-------------|------------------|
| 49 50             | 135 57             | 8.61        | 34.21            | 40 32             | 142 50             | 16.72       | 35.06            |
| 49 27             | 136 19             | 8.22        | 34.06            | 40 08             | 143 23             | 18.06       | 35.41            |
| 49 04             | 136 39             | 8.28        | 34.07            | 39 41             | 143 39             | 17.94       | 35.32            |
| 48 41             | 137 00             | 8.06        | 34.16            | 39 13             | 143 55             | 18.44       | 33.12            |
| 48 17             | 137 21             | 9.44        | 34.42            | 38 48             | 144 15             | 18.44       | 35.51            |
| 47 52             | 137 42             | 9.94        | 34.49            | 38 23             | 144 35             | 19.22       | 35.45            |
| 47 30             | 138 01             | 10.61       | 34.33            | 40 58             | 149 05             | 17.00       | 35.49            |
| 47 04             | 138 18             | 10.56       | 34.58            | 41 23             | 149 48             | 19.89       | 35.65            |
| 46 39             | 138 36             | 10.67       | 34.46            | 41 59             | 151 05             | 19.50       | 35.62            |
| 46 13             | 138 54             | 11.33       | 34.65            | 42 25             | 152 08             | 17.22       | 35.09            |
| 45 48             | 139 08             | 12.56       | 34.79            | 42 51             | 153 13             | 16.94       | 35.15            |
| 45 25             | 139 24             | 12.94       | 34.83            | 43 16             | 154 20             | 16.17       | 35.06            |
| 45 01             | 139 41             | 12.89       | 34.85            | 43 40             | 155 29             | 16.89       | 35.07            |
| 44 24             | 140 07             | 13.56       | 34.69            | 44 00             | 156 37             | 15.94       | 34.86            |
| 44 12             | 140 16             | 13.72       | 35.00            | 44 22             | 157 47             | 16.17       | 34.78            |
| 43 47             | 140 33             | 13.50       | 34.91            | 44 42             | 158 58             | 15.06       | 34.68            |
| 43 23             | 140 50             | 15.39       | 35.03            | 45 02             | 160 10             | 15.00       | 34.69            |
| 42 58             | 141 08             | 15.44       | 35.10            | 45 19             | 161 27             | 15.33       | 34.63            |
| 42 35             | 141 27             | 15.89       | 35.16            | 45 36             | 162 44             | 14.78       | 34.52            |
| 42 11             | 141 41             | 15.56       | 35.13            | 45 52             | 163 58             | 15.39       | 34.71            |
| 41 47             | 141 54             | 16.39       | 35.08            | 46 07             | 165 12             | 14.50       | 34.69            |
| 41 22             | 142 07             | 16.39       | 35.03            | 46 19             | 166 07             | 15.61       | 34.65            |
| 40 57             | 142 25             | 16.94       | 35.17            |                   |                    |             |                  |

## DISCUSSION OF DATA

The most prominent structure apparent in the section (Fig. 2) is that of the East Australian Current. This is described by Deacon (1937) as a southward flowing current of Subtropical Water originating as a branch of the Equatorial Drift deflected by land. According to him, surface Subtropical Water in summer will have a temperature of at least 14.5°C and salinity at least 34.90‰.

Two components of this current are apparent in the latitude of Tasmania. The thermal section indicates its effects to extend to approximately 155° 23' E. This interpretation derives from the requirement that differences in density in a horizontal direction can only exist in the presence of currents and that the water of high density is on the right in the direction of flow in the Southern Hemisphere. In the section, this current appears as a shallow layer with isotherms sloping downward to the left in the direction of flow. Between the two indicated longitudes, the current, on the same premises, has a northward component.

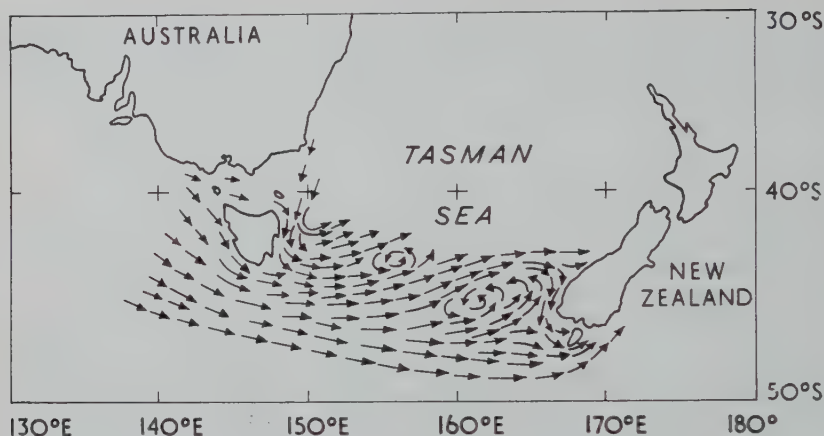


FIG. 3—Currents deduced from the surface observations and thermal section.

Between  $152^{\circ} 08'$  and  $155^{\circ} 29'$  E, to a depth of about 100 ft, the eastern margin of the current appears as an area of weak turbulence and eddies. These were also found by Garner (1954) in his thermograph sections across the Tasman Sea. This area of turbulence seems to continue to  $158^{\circ} 06'$  E, but with varying amounts of water of subantarctic origin becoming apparent. Overlapping this area from  $156^{\circ} 37'$  to  $159^{\circ} 34'$  E is a zone interpreted as the Subtropical Convergence. Surface temperatures and salinities for the eddy area range between  $15.8$  and  $17.1^{\circ}\text{C}$  and from  $34.8$  to  $35.1\text{‰}$  while for the convergence, they range from  $14.8$  to  $16.4^{\circ}\text{C}$  and from  $34.7$  to  $34.9\text{‰}$ . The convergence is poorly developed here and may show only as a shallow, narrow current of Subantarctic Water with a northward component between two areas of weak counter-clockwise eddies. This is inferred from the surface density plot and thermal section across the convergence zone.

From the convergence to  $165^{\circ} 12'$  E, a second region of weak counter-clockwise eddies and turbulence composed of Subantarctic Water with a north-setting current at the eastern margin can be interpreted from the surface data and incomplete bathythermograph observations. This region had surface temperatures from  $14.5$  to  $15.4^{\circ}\text{C}$  and salinities from  $34.5$  to  $34.7\text{‰}$ . At depth, a relatively large and cold tongue of water is evident. This is probably a northward intrusion of Subantarctic Water. Between  $165^{\circ} 12'$  E and the south-west New Zealand coast there appears to be a south-setting current (reported by Deacon, 1937) of mixed subantarctic and coastal water to a depth of at least 200 ft. The characteristics of the main water masses are shown in Table 2.

TABLE 2—Properties of Southern Tasman Sea Waters – February 1959

| Water Body                 | Temperature Range<br>$^{\circ}\text{C}$ | Salinity Range<br>$\text{‰}$ |
|----------------------------|-----------------------------------------|------------------------------|
| 1. Subtropical             | 16.1–20.1                               | 35.0–35.6                    |
| 2. Subantarctic            | 14.5–16.4                               | 34.5–34.8                    |
| 3. Mixed water             | 15.8–17.1                               | 34.8–35.1                    |
| 4. Subtropical Convergence | 14.8–16.4                               | 34.7–34.9                    |

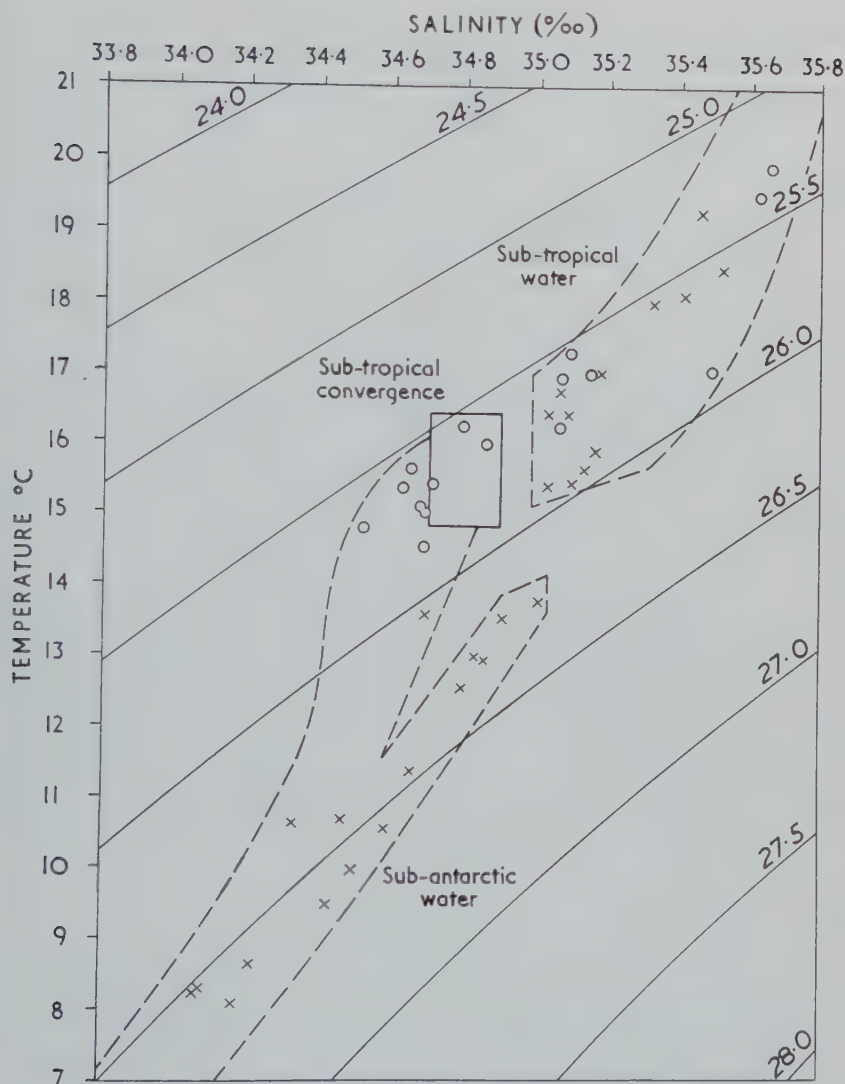


FIG. 4—Temperature-Salinity plot of the observed surface data. Isopleths of constant density ( $\sigma_t$ ) are shown from 24.0 to 28.0.

The Subantarctic Water involved in this section is derived from the area of the West Wind Drift south of Australia (Fig. 3). The surface temperature and salinity data obtained south of Australia (Fig. 4 and Table 1) indicate the presence of Subtropical Water here also so that some admixture between the two has probably occurred by the time the Tasman Sea is

reached. Consequently, the irregularity of temperature and salinity apparent in the surface plots of the Subantarctic Water of the section and its high temperature relative to the equivalent water south of Australia (Fig. 4) is probably not all the result of incomplete mixing in the Tasman Sea eddies.

#### CURRENT INTERPRETATION

The direction of the current component determinable from the data is that which is slightly east of north, due to the location of the section. It is probable that the south-flowing component of the East Australian Current and the weaker inshore current off the south-west coast of New Zealand are cut nearly at right angles by the section. The extension along the section of the northward-flowing component of the East Australian Current together with the associated eddies (Fig. 2) indicates that this portion of the current flows to the north-east. This also applies to the other currents inferred in the south-central Tasman Sea except for those that might have a south-west component due to their counter-clockwise eddy nature. This general north-east set is to be expected from the direction of the prevailing westerly winds. The current structure derived from the surface data and section is shown in Fig. 3. It can be seen from the soundings that no bathymetric control of currents should be expected except near either coast.

The character of the data does not permit an estimate of current speeds to be made. However, it appears that the south-setting component of the East Australian Current is the strongest and that the next strongest is the north-east component. The only other current of any appreciable magnitude is that along the south-west coast of New Zealand. It seems probable that the net surface transfer of Subantarctic Water northward across the section is relatively small. It also appears that, due to the weakness of the Subtropical Convergence here, very little water sinks along this zone and most of that is between the 15 and 16°C isotherms.

#### T-S RELATIONSHIPS

A Temperature-Salinity (T-S) plot of surface values is always open to question because external influences, particularly weather and contamination of the sample from the ship, can modify temperature and salinity values to an extent where interpretation is misleading or erroneous. However, if this is kept in mind and only consistent values considered, the T-S plot can aid greatly to trace water masses and to identify elements of the structure. Here, it shows the change in properties of the Subtropical and Subantarctic water masses with latitude and the values of temperature, salinity and density associated with the Subtropical Convergence.

In Fig. 4, the values of the Tasman Sea surface observations are plotted as circles and those south of Australia as crosses. The rectangle bounds the limiting values previously given for the Tasman Sea Subtropical Convergence and separate observations to the west (Subtropical Water) from those to the east (Subantarctic Water). It is apparent that all values of

surface density for the section, except those in the middle of the East Australian Current, fall between a Sigma-t of 25.5 and 26.0. The consequence of this is the lack of strong currents in the southern Tasman Sea except for the East Australian Current. Furthermore, the values of the Subtropical Convergence south of Australia are evident. The temperature range of the convergence here is approximately 2°C lower and the salinity 0.2‰ higher so that water sinking here is of greater density than that at the Tasman Sea section. This heavier water probably sinks to a lower level and may appear in the section as part of the subsurface, north-east flowing, East Australian Current between the 13 and 15°C isotherms.

#### ACKNOWLEDGMENTS

Accomplishment of these observations would not have been possible without the services of the Bathythermograph Team assigned to the ship for the operation or without the assistance and cooperation of the officers and crew. The assistance and criticism of the manuscript by Dr R. W. Burling, N.Z. Oceanographic Institute, was highly appreciated.

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## TSUNAMI WARNING CHARTS

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(Received for publication, 11 November 1960)

### Summary

Two charts have been constructed to assist in predicting the travel times of tsunami waves reaching the New Zealand coast from known origins. If the time and location of the generating earthquake are known, the initial wave arrival times at various points on the coast lying in the direct path of the tsunami can be estimated within a time of approximately one hour.

### INTRODUCTION

Long waves in the sea, such as tsunami waves, are known to travel at a speed  $v$  given to a good approximation by the formula  $v = \sqrt{gh}$  where  $g$  is the acceleration of gravity and  $h$  is the depth. If a wave diagram is drawn, e.g., by Huyghen's construction, for waves spreading out from a point  $P$ , then the time of travel between  $P$  and any other point  $P'$  can be found. By the principle of the reversibility of rays, part of a circular wave front spreading out from  $P'$  will follow the same path, but in the opposite direction, from  $P'$  to  $P$ . The travel time will be the same in either direction. In the case of a small island, travel times for tsunami waves from any point in the surrounding sea may be found by drawing a wave diagram for an imaginary wave which spreads out from the island. Charts of a slightly different nature are required to predict travel times between an arbitrary point in the sea and various points on the coast of a large island, unless a separate chart is drawn for each coastal point of interest. Compromises must be made in selecting the charts to be constructed.

In the present case two charts have been selected for construction. The first chart gives the travel time in hours for tsunami waves originating at points further than 600 nautical miles from Wellington to reach a circle  $C$  of 600 nautical miles radius centred on Wellington, assuming that the waves cross  $C$  perpendicularly. It is to be noted that the latter assumption will apply, in general, only to that portion of the tsunami wave front which first crosses  $C$  at a point  $P'$  say.

The second chart shows the travel time from  $C$  to the coast of New Zealand for those portions of an imaginary wave front initially coinciding with  $C$  which reach the coast in a minimum of time. As explained below, this chart is to be used as a guide in estimating travel times to the coast for a real wave front initially touching  $C$  at some point.

### DESCRIPTION OF CHARTS

An equidistant azimuthal projection (N.Z. Lands & Survey Map, N.Z.M.S. 47, 1953, 1 : 90,000,000) has been used in Fig. 1. Hence any straight line drawn through Wellington represents a great circle path. A line drawn

# GILMOUR - TSUNAMI WARNING CHARTS

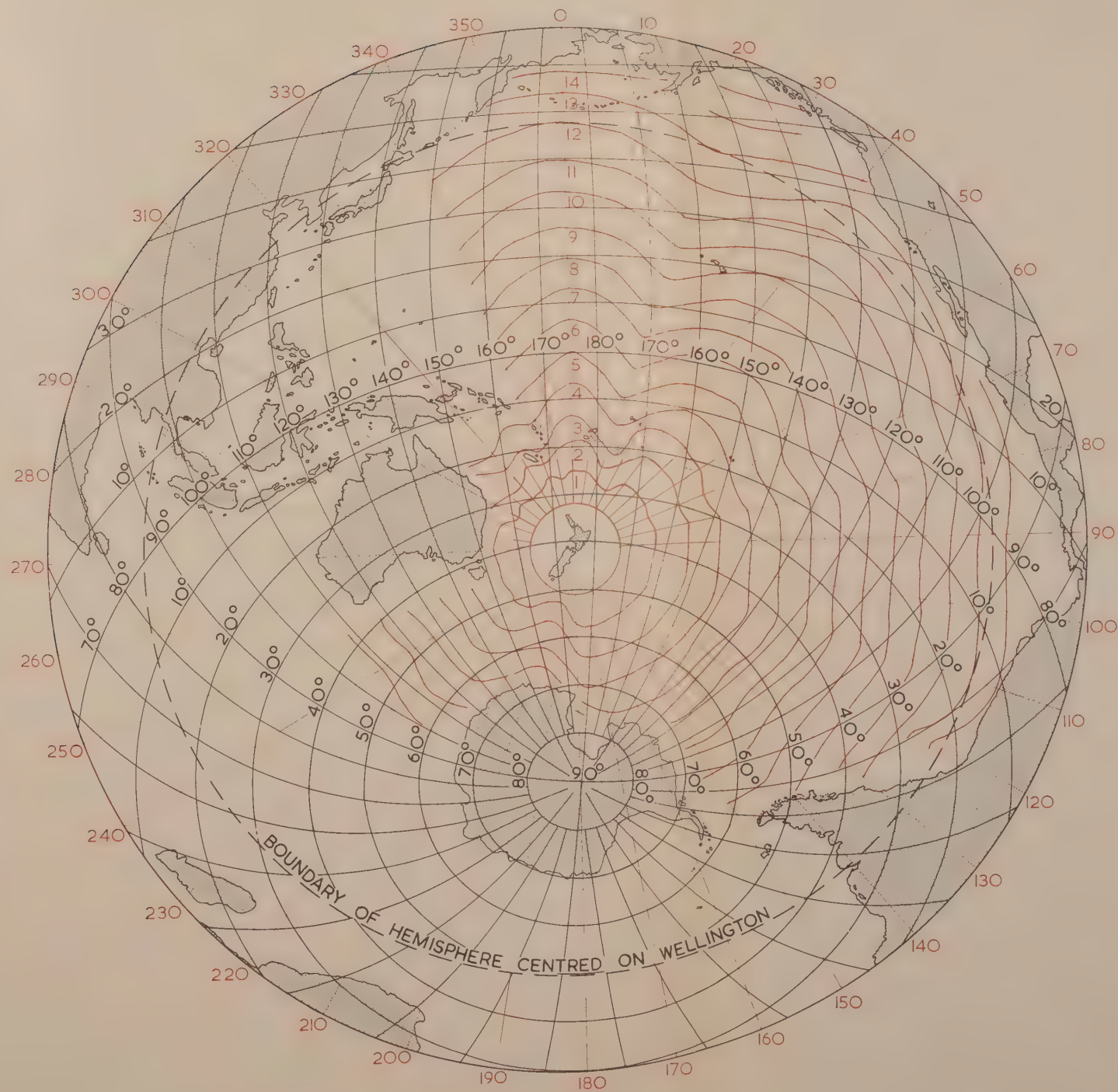


FIG 1.—Travel time, in hours, of Tsunami waves originating at points further than 600 nautical miles from Wellington to reach a circle of 600 nautical miles radius centred on Wellington.



# GILMOUR - TSUNAMI WARNING CHARTS

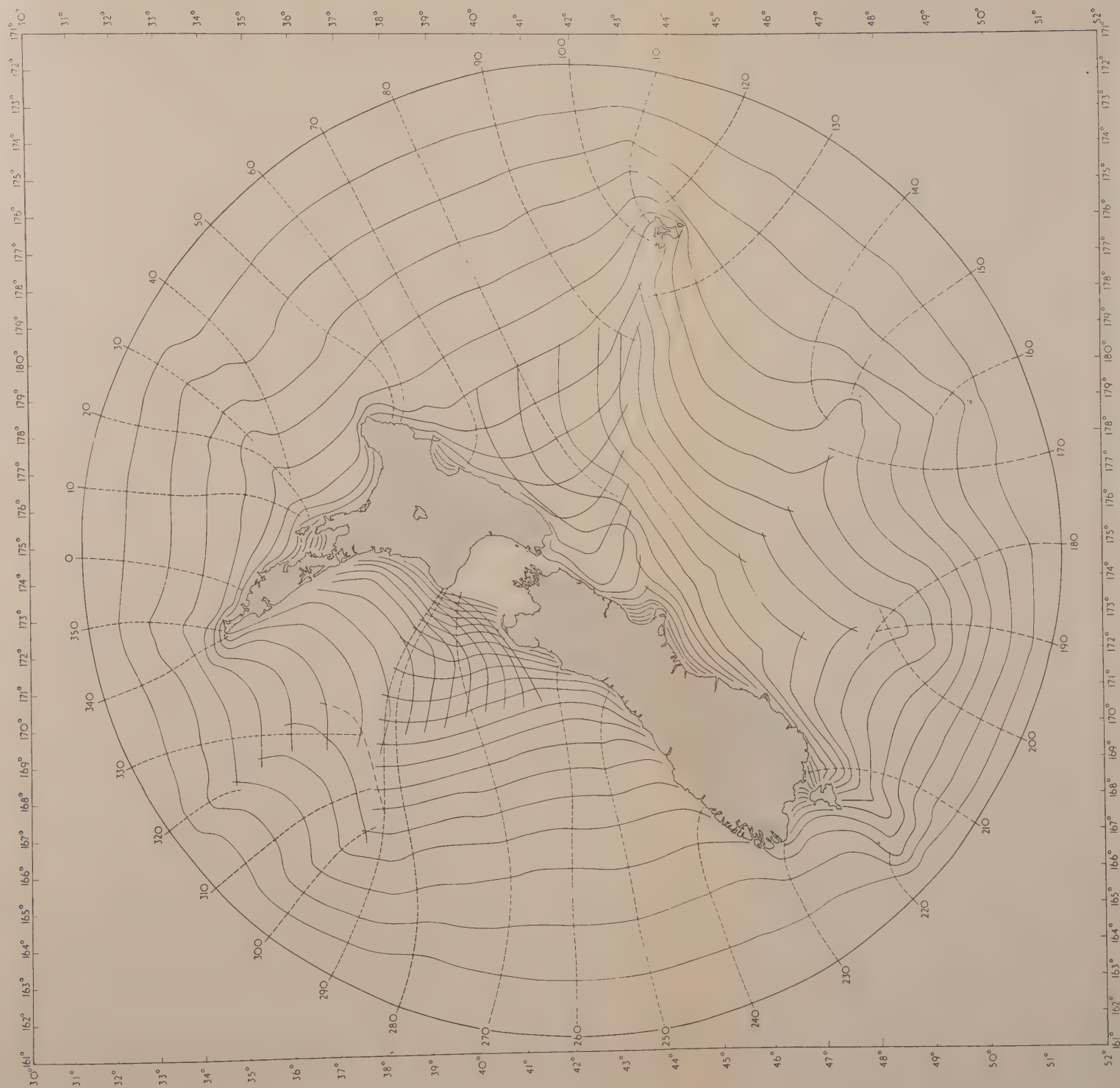


FIG 2—Travel time of a Tsunami wave from a circle 600 nautical miles radius from Wellington to the New Zealand coast. The successive positions of the wave at 10-minute intervals from coincidence with the circle are shown.



between the point of tsunami origin and Wellington is assumed to be the ray along which that part of the wave front which first crosses C will travel. This assumption results in a first approximation to the true wave diagram for the circumstances under consideration.

Data for the chart (Fig. 1) were obtained by finding the travel times along 36 great circle paths radiating from Wellington. From the formula for wave speed, the time to travel a small distance  $\Delta s$  is  $\Delta t = (\Delta s)/\sqrt{gh}$ . A value of 60 nautical miles was taken for  $\Delta s$  and a suitable value for  $h$  was selected for each path segment  $\Delta s$ . Depths were taken mainly from the series *General Bathymetric Charts of the Oceans*, 3rd edition, published by the International Hydrographic Bureau, Monaco. These charts were supplemented by others, notably chart number 2562 published by the U.S. Hydrographic Office.

Fig. 2 shows successive positions at 10-minute intervals of a wave front moving towards New Zealand from an initial coincidence with C. Graphs for selected depths were first drawn giving the Mercator chart distance that a tsunami wave would travel at various latitudes in 10-minute periods. Using Huygen's construction the original chart for Fig. 2 was then drawn on a Mercator chart with a scale of  $1^\circ$  of longitude to an inch. Bathymetry was taken mainly from the U.S.H.O. charts 2562 and 6710, and also from charts drawn by the New Zealand Oceanographic Institute (Bathymetric Charts, 1960, 1 : 2,191,400 (at Lat.  $0^\circ$ ) North Island, New Zealand, and South Island, New Zealand).

Refraction results in distortion of wave fronts. Overlapping occurs in Fig. 2 although in most cases the overlapping wave fronts have not been drawn. Attention has been concentrated on wave fronts which reach the coast in a minimum of time.

Ray paths are represented by curves which are orthogonal to the wave fronts. Some orthogonals (dotted curves in Fig. 2) are shown. Many of these have not been completed because the overlapping wave fronts have not been drawn.

The distance between wave fronts in Fig. 2 measured along orthogonals also indicates approximately, for a particular locality, the distance which a wave will travel during ten minutes, no matter in which direction it is travelling.

#### USE OF THE CHARTS

The azimuth of the point I at which the wave front is assumed to cross C first can be found by drawing a straight line between the tsunami origin point and Wellington. The travel time from the origin point to I can be found by interpolating between the curves in Fig. 1 which correspond to hourly intervals.

An incident wave front touching C at the position of I is drawn on Fig. 2. Approximate ray paths can then be drawn between corresponding points on the coast and the wave front using Fig. 2 as a guide to refraction effects. From these ray paths and the spacing of the wave fronts in Fig. 2 (corresponding to 10-minute intervals), approximate travel times can be

found for various points on the coast, from the time when the tsunami wave front initially touches C to the time when a wave front arrives at the chosen point on the coast.

The sum of the two travel times found from Figs. 1 and 2 for any point on the coast must be added to the occurrence time of the earthquake (normally given in G.M.T.) to obtain the predicted arrival time.

### ERRORS

Real ray paths accord with Fermat's principle of minimum (or extremum) time. However, in drawing Fig. 1 it has been assumed that waves travel along great circle paths. This assumption is not completely correct unless the sea is uniformly deep.

Small increases in path length can accommodate quite large changes both in the actual path and in the azimuth (from Wellington) of the point I' of initial contact between an advancing wave front and C. As an example consider the curve S' defined by the equations  $r = R$  and  $\varphi = (2\kappa \cos \theta)/r$  which lies on a sphere of radius R and passes through the points A (R, 0,  $\varphi$ ) and B (R,  $\pi/2$ , 0), where  $r$ ,  $\theta$ ,  $\varphi$ , are spherical polar co-ordinates and  $\kappa$  is a parameter. The great circle arc S from A to B (defining equations:  $r = R$ ,  $0 \leq \theta \leq \pi/2$ ,  $\varphi = 0$ ) has a length equal to one quadrant. If  $\theta = \pi/4$ , S' attains its maximum separation  $\kappa$ , measured on the sphere surface, from S. The tangents to S and S' at A (and B) intersect at an angle of  $(2\kappa)/r$  radians. With  $(2\kappa)/r$  radians equal to  $18^\circ$  it was calculated that S' is only 1.9% longer approximately than S although the maximum separation  $\kappa$  between S and S' is 0.10 quadrant. With  $(2\kappa)/r$  radians equal to  $25.5^\circ$  the corresponding figures are 3.5% and 0.14 quadrant approximately.

Since the wave velocity is proportional to the square root of the depth, a wave travelling from X to Y, say, by a path  $x\%$  longer than the great circle path, must be able to find a path for which the mean depth is at least  $2x\%$  (approximately) greater than the mean depth over the great circle path.

Because the depth of the Pacific basin is fairly uniform the time of travel between a point of tsunami origin and C is unlikely to be more than a few per cent less than the travel time computed over a great circle path. However, actual arrival times will tend to be earlier than those predicted from Fig. 1.

Errors in the depths used in calculating the travel times over great circles will also affect the accuracy. Because the depth errors will be fairly random the cumulative effect will not lead to large percentage errors. It is estimated that Fig. 1 will give the travel times over long distances within 5% in most cases.

The radius for each Huyghen's circle drawn in constructing Fig. 2 and the appropriate mean value of  $h$  over the circle radius are interdependent. Errors occur in approximating to the required circle radii. Error also arises from the finite size of the Huyghen's circle radii and from the finite number of circles drawn.

However the errors incurred in the practical use of Fig. 2 are more important than inaccuracies in the drawing since Fig. 2 must be used for estimating travel times for wave fronts which do not initially coincide with the large segments of C.

The point I' at which the wave front initially touches C is uncertain to some degree. From the example already given it can be seen that the difference in the azimuths of I' and I (see above) could differ by  $20^\circ$  with only moderate changes (approximately 5% say) in sea depths between neighbouring regions.

The time between the instant when the wave front crosses C and the arrival of a wave at any point on the directly exposed coast should be estimable to within 30 minutes.

#### APPLICATION TO THE CHILEAN EARTHQUAKE OF MAY 1960

Data published by the U.S. Coast and Geodetic Survey (1960) report that the destructive tsunami on this occasion originated from an earthquake occurring at a position  $38^\circ$  S,  $73^\circ 30'$  W at 1911 G.M.T. on 22 May 1960.

From Fig. 1 it was estimated that the wave would first touch C at a point I with azimuth  $130^\circ$  and at a time 11 hours after the earthquake. From Fig. 2 it was estimated that the initial waves would reach Wellington and Otago harbours at times 140 and 120 minutes later respectively. Therefore, the arrival times hindcast for 23 May at Wellington and Otago harbours are 0830 G.M.T. (2030 N.Z.S.T.) and 0810 G.M.T. (2010 N.Z.S.T.) respectively.

Both the Wellington and Otago harbour gauges showed the first signs of tsunami waves at approximately 1940 N.Z.S.T. The arrival times hindcast are therefore 50 and 30 minutes later than the actual arrival times. These errors are reasonable in view of the errors already discussed.

#### ACKNOWLEDGMENTS

Thanks are expressed to Mr N. F. Barber of the Dominion Physical Laboratory, D.S.I.R., for helpful discussions, and to the Wellington and Otago Harbour Boards for the use of records.

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## BENEFICIATION OF MANGANESE ORES WITH PARTICULAR REFERENCE TO THE TREATMENT OF A LOW GRADE ORE FROM VITI LEVU, FIJI

By M. H. BUCKENHAM, Faculty of Technology, University of Otago.

*(Received for publication, 10 November 1960)*

### Summary

Because of the increasing demand for manganese and the depletion of high-grade deposits considerable attention is now being directed at beneficiation of low-grade manganese ores. Most manganese ores due to their complex mineral association and their variable physical characteristics present many beneficiation problems some of which cannot be overcome satisfactorily.

The manganese deposits of Fiji are becoming increasingly important but before many of them can be exploited a cheap beneficiation process will be required. Test work on a sample of ore from a low-grade deposit in S.W. Viti Levu showed that a marketable manganese concentrate could not be produced from this ore by gravity concentration or flotation even though a low manganese recovery may be acceptable. The poor metallurgical results were due to the reasons mentioned above and because the ore contained an appreciable percentage of iron oxides. Iron oxides and manganese oxides have very similar physical and chemical properties and therefore cannot be separated satisfactorily by gravity concentration or flotation.

### INTRODUCTION

Steel is fundamental to an industrial economy and manganese is essential to steel production. Unless revolutionary changes take place in the steel-making process manganese will remain an essential material. Manganese is also important as a non-ferrous alloying element, has important chemical uses, and as  $MnO_2$  is essential in the manufacture of dry batteries. Tonnages for these latter uses are small compared with quantities used in the steel industry but the requirements are nevertheless important.

World reserves of high-grade manganese ores are estimated to approximate 1 billion tons, at least two-thirds of which lie in the U.S.S.R. and associated countries. The United States of America, perhaps the greatest consumer, excluding U.S.S.R., has extensive low-grade refractory manganese deposits but very little high-grade ore. India, Africa, and South America provide most of the United States imports.

The main problem of the world's manganese industry at the present time is the need for high-grade ore deposits which can be exploited relatively cheaply to provide manganese at reasonable prices. With the general drop in grade of the manganese ores available, however, industry has found it necessary to lower the grade of ferromanganese produced while at the same time steels of higher and more rigid specifications are required. There is as a result a great need to develop methods of exploiting and more particularly beneficiating low-grade deposits so that the demanding needs in terms of both quantity and quality of product can be met.

Because of the increasing demand for manganese, the manganese deposits of Fiji have been the subject of considerable attention in recent years. These deposits, although relatively small by world standards, could make a significant contribution to the production of manganese in the free world.

Market specifications for manganese vary, but ores and concentrates over 40% Mn (63.3  $\text{MnO}_2$ ) usually find a market if other constituents are acceptable. For chemical and metallurgical purposes ores or concentrates approaching 50% Mn (79.1%  $\text{MnO}_2$ ) are preferred and for use in the latter industry iron oxide, silica, and phosphorus contents should be low. At the time of the present investigation Fijian buyers were quoted as accepting ores or concentrates containing 50% manganese and less than 9% silica with penalties above 4% silica and 5% iron. Low-grade ore with a minimum of 40% manganese was acceptable at a considerably lower price if silica and iron contents were below 10% and 15% respectively.

In addition to the grade requirements a size limit may have to be met by ores and concentrates. This generally stipulates an upper size limit (12 in.) and a percentage of plus 20 mesh material (often 75%). Finely sized ores or concentrates must therefore be blended with coarser ores or sintered. Sintering although increasing production costs increases the manganese content by removing oxygen, carbon dioxide, water, and other volatiles. Unfortunately iron and silica percentages are increased at the same time, and sintering, apart from meeting sizing requirements, is only of real value with carbonate ores.

#### METHODS OF TREATING MANGANESE ORES

The milling and beneficiation of manganese ores has only recently, with the depletion of the high-grade ores, assumed commercial importance. Up to the present time the large higher grade deposits have required only simple processing and conventional methods of beneficiation have been important only in the treatment of marginal deposits and under abnormal market conditions. Although many methods of beneficiating low grade ores have been investigated (Norcross, 1940; Schack and Poole, 1947; McCarroll, 1954; Engel, *et al.*, 1955; Fine and Frommer, 1956; Buckenham, 1957; and Gates, 1957), no generally accepted method of treatment has been established because of the different physical characteristics and mineral associations in ores from different localities. As a result a particular method of treatment may be of value only in a restricted geographical area and therefore not suitable for large scale and economic application.

In some ores the manganese minerals occur as relatively large aggregates whereas in others impurities are uniformly and intimately distributed throughout the manganese minerals as particles a few microns in size. Some ores are tough and hard, others soft and friable, and many are mixtures of both types, particularly those in which high grade and marginal areas occur in the one deposit.

Investigations into methods of treating manganese ores have involved:

- (a) Mechanical concentration including gravity, flotation, and magnetic methods;

- (b) Hydrometallurgical extraction in which chemical leaching is required;
- (c) Pyrometallurgical extraction employing some form of smelting technique.

Of these, physical methods of treatment are the most attractive economically, and appear to have the greatest potential at the present time. Neither hydro nor pyrometallurgical processing can yield a product in any way competitive with that produced from the naturally occurring high-grade ores, but these methods often overcome the problems presented by some of the complex mineral associations common in manganese ores: smelting can, for example, be used for direct production of silico- and ferromanganese.

The ores of manganese may be broadly classified as oxide, carbonate, silicate, and complex. Psilomelane and pyrolusite ores are the most common oxide ores and when these minerals are associated with quartz or silicate gangue they are readily concentrated. They become difficult and often impossible to treat if iron oxides are the chief gangue constituents. Iron oxides are chemically allied to manganese oxides and have many similar physical properties. Oxide ores containing wad and manganite as the principal manganese minerals are not readily amenable to concentration. Wad – a mixture of unidentifiable manganese oxide minerals with lime, clay, and iron minerals – is very soft and on grinding disintegrates into untreatable slimes. Manganite on the other hand is usually crystalline but the crystals are needle-like and friable.

Rhodochrosite is the only manganese carbonate mineral of economic importance and its occurrence to any significant extent is rare. It responds readily to concentration by flotation. Silicate ores are of very minor importance as a source of manganese also, although the occurrence of rhodonite in ores is common. This mineral, however, rarely contains more than 30% manganese. Braunitz is sometimes found in many cherty, siliceous manganese oxide ores and this mineral containing 10% silica behaves as the oxide minerals in treatment. A group of oxide manganese ores characterised by the impregnation of chert, chalcedony, or opal, by psilomelane or pyrolusite may be classified as silicate ores. Effective concentration of these ores is difficult and attempts usually are confined to the separation of the rich from the poor manganese components with the recovery of only a small percentage of the contained manganese.

Complex ores include those containing mixed oxide, silicate, and carbonate manganese minerals and those which are complex as a result of their intimate mineral association. These ores are generally most difficult to treat as effective liberation of constituents is rarely possible at a size sufficiently coarse for concentration. The most common type of complex ore is that containing iron oxides and, except perhaps for flotation involving costly and complex reagents, magnetic concentration following a reducing roast is the only possible method of treatment.

Gravity concentration (heavy medium, tabling, and jigging), froth flotation, agglomeration tabling or table flotation, and magnetic concentration are beneficiation processes used in the treatment of manganese ores. Careful control of crushing, grinding, and sizing is an essential prerequisite to successful physical concentration. Ores which contain slime forming constituents such as clay, iron ochre, and wad together with harder gangue constituents,

often require preliminary washing before further treatment but this may lead to extensive manganese losses in the form of slimes. In some instances slime forming gangue may be selectively removed by washing.

## MANGANESE IN FIJI

### *General*

Manganese in Fiji has been known for a considerable time but until about 1948 no attempt had been made to develop any of the deposits. The deposits are frequent and widespread and spectacular developments in production and discovery have resulted in recent years. Methods of production are primitive and selective mining and irregular production in terms of both quantity and quality is characteristic. Production at the present time by world standards is very small but both chemical and metallurgical grades of ore can be produced without difficulty. In addition to the higher grade ores at present exploited extensive deposits of marginal and low grade deposits exist. Ready markets have always been found in the United Kingdom for Fijian manganese and markets in Australia and the United States would exist if regular and increased tonnages could be produced.

It could well be the subgrade deposits in Fiji which in the future contribute largely to the overall production as these deposits could be readily exploited if suitable and relatively cheap beneficiation processes were developed. Some difficulties in addition to those associated with processing would, however, need to be overcome, the most important of which is the inaccessibility of so many of the deposits. Few deposits are close to the present roading system and all-weather access in most cases is impossible. In addition handling and shipping facilities would require improvement.

### *Geology and Mineralogy*

The geology of the manganese deposits of Fiji has not been reported in any detail although a programme of examination is in progress (Taylor, 1953). cursory examinations of the deposits have revealed that they are irregular in distribution and generally underlain with deeply weathered red and yellow clays. Silicification in the form of jasper is evident and mineralisation indicates faulting before ore formation. Two types of deposit occur:

- (a) Secondary concentrations from pre-existing rock masses of relatively high manganese content;
- (b) Silicified replacement deposits in which andesites, tuffs, and agglomerates have been replaced by silica and manganese in fracture zones near the surface.

The main manganese minerals are psilomelane and pyrolusite but wad and hausmannite are frequently present. The ore minerals occur in veinlets, veins, irregular bodies, and masses, and are often found in association with limestone and barytes. Mineralised zones are small. Large quantities of quartz and iron oxides are associated with manganese minerals, common associations ranging from a few per cent manganese with 85–90% silica and 10–15% iron to 60% manganese with only 1% iron oxide and silica.

In the S.W. part of Viti Levu numerous small mines have been developed (Skiba, 1954). The Adams No. 4 mine, ore from which was tested in this investigation, is one of a number of mines situated close to the present roading system about five miles from the coast at Momi Bay and less than 10 miles south of Nadi. The Adams No. 4 mine is situated in hilly country and ore is evident in a face some hundred feet high and about a quarter of a mile long. Tonnage estimates are between 20 and 30 thousand tons and the sample selected for testing was described as being lower than average grade but typical of the poorer ore in the deposit.

#### TEST WORK ON ORE FROM ADAMS NO. 4 MINE, FIJI

##### *Preliminary Examination of Ore*

Hand specimen examination showed that the ore submitted for testing varied widely in its physical nature and in its mineralogical composition. Fragments examined varied from very hard siliceous material to soft friable earthy material. The mixture of minerals in all specimens examined appeared intimate and complex, although in some instances coarse associations of manganese oxide minerals contained in particular pyrolusite were identified. Silicification in the form of jasper was evident in some specimens.

The soft and friable components of the ore were identified as wad and the iron oxides as limonite and hematite. Microscopic examination of polished specimens showed the presence of quartz and iron oxides in addition to the manganese minerals, pyrolusite, manganite, and hausmannite and a fine grained groundmass also containing manganese.

The pyrolusite, strongly anisotropic, appeared in the form of fine grained aggregates and irregular blebs up to  $600\ \mu$  in size. Pyrolusite was also observed in intimate association with manganite and to a lesser extent hausmannite. Some of the pyrolusite appeared to have replaced manganite and was in grains less than  $30\ \mu$  in size. Manganite, also strongly anisotropic but showing less reflectivity than pyrolusite, was observed in lamellar crystalline aggregates. These aggregates often showed a radiating texture and consisted of needle like crystals of manganite. Although a few large grains of manganite were observed this mineral was generally well below  $150\ \mu$  in grain size. Deep red internal reflection colours confirmed the presence of hausmannite, most of which appeared in grains less than  $100\ \mu$  in size. Examination of the ground mass under high power revealed distinct grains of pyrolusite, manganite, hausmannite and quartz in most intimate association. Quartz also appeared in the ore as relatively coarse grains up to  $200\ \mu$  in size. Some quartz like material, red in colour, was identified as chalcedony or jasper common minerals in complex manganese ores. Few grains of the iron oxides were observed in the polished specimens, no doubt, due to the selection of harder fragments of ore for the microscopic examination.

The most noticeable feature of the ore as revealed by the hand specimen and polished specimen examinations was the extreme complexity of its mineral association. The grain size in the fragments examined was small and uneven, and intergrowths between the constituent minerals were common. Although on first inspection many of the manganese minerals appeared to be

in grains of relatively large size these on closer examination were found to be aggregates of much smaller grains which would readily break down to fine sizes on treatment and be difficult to recover.

On the basis of the hand specimen and microscopic examination it was concluded that the ore from the Adams No. 4 mine would present most of the usual problems associated with the beneficiation of low grade complex manganese ores. It was evident that a high recovery of manganese in a concentrate meeting market specifications as regards manganese content could not be expected, but there appeared a possibility of recovering at least half of the manganese in such a product. It was also apparent that it would not be possible to achieve substantial liberation of the ore components even after fine grinding which in turn would slime the soft, earthy, and friable components of the ore. In addition, an effective separation between the iron and manganese oxide minerals could not be expected.

### Gravity Concentration

The ore which assayed 20.6% manganese ( $32.6 \text{ MnO}_2$ ), 15.5% iron, and 34.3% acid insoluble was sampled and a representative portion crushed to minus  $\frac{1}{2}$  in. and sized on  $\frac{3}{16}$  in. and 10 mesh\* screens. The two coarsest size fractions were subjected to sink float analyses in a bromoform - carbon tetrachloride mixture of specific gravity 2.80.

The manganese distribution in the crushed product and in the sink float products is shown in Tables 1 and 2.

TABLE 1—Sizing Analysis and Manganese Distribution in Ore Crushed to Minus  $\frac{1}{2}$  in.

| Size Fraction                                 | Wt %   | Assay %Mn | Distribution %Mn |
|-----------------------------------------------|--------|-----------|------------------|
| — $\frac{1}{2}$ in. + $\frac{3}{16}$ in. .... | 36.48  | 19.3      | 34.1             |
| — $\frac{3}{16}$ in. + 10 mesh .....          | 33.99  | 20.5      | 33.8             |
| —10 mesh .....                                | 29.53  | 22.4      | 32.1             |
| Calc. head .....                              | 100.00 | 20.6      | 100.0            |

TABLE 2—Manganese Distribution in Sink and Float Products After Separation at S.G. 2.80

| Size Fraction                            | Treatment               | Product    | Wt %   | Assay %Mn | Distribution %Mn |
|------------------------------------------|-------------------------|------------|--------|-----------|------------------|
| — $\frac{1}{2}$ in. + $\frac{3}{16}$ in. | Sink float at S.G. 2.80 | Float      | 23.96  | 8.1       | 10.1             |
|                                          |                         | Sink       | 76.04  | 22.8      | 89.9             |
|                                          |                         | Calc. head | 100.00 | 19.3      | 100.0            |
| — $\frac{3}{16}$ in. + 10 mesh           | Sink float at S.G. 2.80 | Float      | 8.94   | 5.4       | 2.3              |
|                                          |                         | Sink       | 91.06  | 22.0      | 97.7             |
|                                          |                         | Calc. head | 100.00 | 20.5      | 100.0            |

\*Tyler screens were used throughout the investigation.

From these results it may be calculated that 11.59% of the ore could be rejected by sink float separation at a specific gravity of 2.80 after crushing to minus  $\frac{1}{2}$  in. The manganese loss would be 4.2%. It is apparent from the results that sink float separation would not be applicable as a preliminary upgrading step in the treatment of the ore although separations were made at only one S.G. At a lower S.G. a lesser percentage of the ore would be rejected and at a higher S.G. more manganese would be lost. As the float product from the finer size fraction was the lower in manganese – 5.4% compared with 8.1% – it may be concluded that the more effective liberation of siliceous gangue components was obtained at this size. The greater weight of the coarser float product (23.96% compared with 8.94%) indicates that more gangue is in this size fraction. This would be expected due to tendency of the other minerals, which would be softer, to crush preferentially.

In preparation for jigging and table concentration a representative portion of the minus  $\frac{1}{2}$  in. ore was crushed to minus 10 mesh. The sample was deslimed hydraulically before screening on 10, 20, and 35 mesh screens. The manganese distribution in the crushed product and in the products resulting from concentration is shown in Tables 3 and 4.

TABLE 3—Sizing Analysis and Manganese Distribution in Ore Crushed to Minus 10 Mesh

| Size Fraction | Wt %   | Assay %Mn | Distribution %Mn |
|---------------|--------|-----------|------------------|
| –10 + 20 mesh | 47.17  | 20.8      | 46.0             |
| –20 + 35 mesh | 22.34  | 21.7      | 22.7             |
| –35 mesh      | 24.62  | 22.3      | 25.7             |
| Slime         | 5.87   | 20.1      | 5.6              |
| Calc. head    | 100.00 | 21.3      | 100.0            |

TABLE 4—Manganese Distribution in Products Resulting from Jig and Table Concentration

| Size Fraction | Treatment | Product     | Wt %   | Assay %Mn | Distribution %Mn |
|---------------|-----------|-------------|--------|-----------|------------------|
| –10 + 20 mesh | Jigging   | Concentrate | 4.63   | 43.6      | 9.7              |
|               |           | Middling    | 14.26  | 38.3      | 26.3             |
|               |           | Tailing     | 81.11  | 16.4      | 64.0             |
|               |           | Calc. head  | 100.00 | 20.8      | 100.0            |
| –20 + 35 mesh | Tabling   | Concentrate | 13.90  | 38.5      | 24.7             |
|               |           | Middling    | 18.87  | 26.1      | 22.8             |
|               |           | Tailing     | 67.23  | 17.0      | 52.5             |
|               |           | Calc. head  | 100.00 | 21.7      | 100.0            |
| –35 mesh      | Tabling   | Concentrate | 25.12  | 36.3      | 40.8             |
|               |           | Middling    | 36.01  | 20.2      | 32.5             |
|               |           | Tailing     | 38.87  | 15.3      | 26.7             |
|               |           | Calc. head  | 100.00 | 22.3      | 100.0            |

The recovery of manganese in these tests is low considering the grade of concentrates produced. Table 5, a metallurgical statement combining the gravity concentration tests on the basis of the sizing analysis of the minus 10 mesh ore, shows that only 32.7% of the manganese in the ore was recovered in a concentrate assaying 38.2% manganese. Assuming that the manganese in the middling products from these tests could be upgraded to 38.2% without loss of manganese the recovery would still remain below 50%.

TABLE 5—Metallurgical Statement Combining Gravity Concentration Test Results on a Weighted Basis

| Product                         | Wt<br>% | Assay<br>%Mn | Distribution<br>%Mn |
|---------------------------------|---------|--------------|---------------------|
| —10 + 20 mesh concentrate ..... | 8.91    | 39.6         | 16.6                |
| —20 + 35 mesh concentrate ..... | 3.11    | 28.5         | 5.6                 |
| —35 mesh concentrate .....      | 6.18    | 36.3         | 10.5                |
| Combined concentrate .....      | 18.20   | 38.2         | 32.7                |
| —10 + 20 mesh middling .....    | —       | —            | —                   |
| —20 + 35 mesh middling .....    | 4.22    | 26.1         | 5.1                 |
| —35 mesh middling .....         | 8.86    | 20.2         | 8.4                 |
| Combined middling .....         | 13.08   | 22.1         | 13.5                |
| —10 + 20 mesh tailing .....     | 38.26   | 16.4         | 29.5                |
| —20 + 35 mesh tailing .....     | 15.02   | 17.0         | 12.0                |
| —35 mesh tailing .....          | 9.57    | 15.3         | 6.7                 |
| Combined tailing .....          | 62.85   | 16.4         | 48.2                |
| Slime fraction .....            | 5.87    | 20.1         | 5.6                 |
| Calc. head .....                | 100.00  | 21.3         | 100.00              |

Perhaps the most significant feature of all the gravity concentration tests is that in no case was a tailing low in manganese produced. This of course supports the observations made during mineragraphic examination and indicates that only the portion of the manganese in relatively coarse association was recovered in the gravity concentrates, and that the more intimately associated and finely disseminated manganese minerals reported in the tailing. The relatively low grade of the concentrates would be due, in part, to the recovery of iron oxide minerals of similar specific gravity to the manganese oxides.

### Flotation

Froth flotation has been used with success in the treatment of manganese ores and is perhaps the most selective method available for the recovery of manganese from complex mineral associations. The flotation tests reported in Table 6 are typical of a large number of tests carried out in this investigation in an endeavour to develop suitable flotation conditions and reagent combinations.

TABLE 6—Manganese Distribution in Products Resulting from Concentration by Flotation

| Flotation Conditions        | Product        | Wt %   | Assay % Mn | Distribution % Mn |
|-----------------------------|----------------|--------|------------|-------------------|
| Grind 55% minus 200 mesh    |                |        |            |                   |
| Oleic acid 2.0 lb/ton       | Concentrate    | 40.72  | 25.85      | 50.1              |
| Sod. silicate 4.0 lb/ton    | Tailing        | 59.28  | 17.65      | 49.9              |
| Sod. oxalate 4.0 lb/ton     | Calc. head     | 100.00 | 21.00      | 100.0             |
| Sod. hydroxide 2.0 lb/ton   |                |        |            |                   |
| Grind 70% minus 200 mesh    |                |        |            |                   |
| Sod. oleate 2.0 lb/ton      | Concentrate 1  | 24.08  | 20.5       | 24.9              |
| Sod. silicate 4.0 lb/ton    | Concentrate 2  | 20.37  | 24.1       | 24.8              |
| Neo-Fat 1-65** 0.5 lb/ton   | Tailing        | 55.55  | 17.9       | 50.3              |
| Fuel oil 17.0 lb/ton        | Calc. head     | 100.00 | 19.8       | 100.0             |
| A C Reagent 708 1.0 lb/ton  |                |        |            |                   |
| Soda ash 8.0 lb/ton         |                |        |            |                   |
| Grind 80% minus 200 mesh    |                |        |            |                   |
| Sod. oleate 0.5 lb/ton      | Concentrate 1. | 12.86  | 18.9       | 11.9              |
| Sod. silicate 4.0 lb/ton    | Concentrate 2  | 28.04  | 25.1       | 34.4              |
| Armac C.D.† 0.1 lb/ton      | Concentrate 3  | 33.92  | 22.7       | 37.7              |
| A C Reagent 708‡ 0.8 lb/ton | Concentrate 4  | 7.68   | 14.2       | 5.3               |
| Fuel oil 30.0 lb/ton        | Tailing        | 17.50  | 12.5       | 10.7              |
| Soda ash 6.0 lb/ton         | Calc. head     | 100.00 | 20.4       | 100.0             |
| Grind 60% minus 200 mesh    |                |        |            |                   |
| Oleic acid 20.0 lb/ton      | Concentrate* 1 | 66.60  | 24.8       | 75.8              |
| Sod. silicate 8.0 lb/ton    | Concentrate 2. | 6.20   | 25.9       | 7.4               |
| Sod. oxalate 4.0 lb/ton     | Tailing        | 27.20  | 13.5       | 16.8              |
| Sod. hydroxide 2.0 lb/ton   | Calc. head     | 100.00 | 21.8       | 100.0             |

\* This concentrate on refloating assayed 31.9% manganese. Manganese recovery 15.1%.

\*\* Stearic acid manufactured by Armour and Co.

†Coco amine acetate manufactured by Armour and Co.

‡Vegetable fatty acid manufactured by American Cyanamid Co.

The tests reported in Table 6 show that a marketable manganese concentrate could not be produced by flotation and that in no instance was a low grade tailing rejected even though grinding as fine as 80% minus 200 mesh was tested. The low grade of concentrate was again due to the non selectivity between iron and manganese oxides and the tendency of the readily slimed minerals to float under the strong frothing conditions encountered with the carboxylic type collectors used. Although finer grinding may have enabled a lower manganese tailing to be produced this would in turn have produced more slimes and probably lower concentrate grades.

One test to investigate the suitability of table flotation or agglomeration tabling in the treatment of the ore was conducted. This concentrating process has been found successful in treating manganese ores and has the advantage over froth flotation of upgrading a coarser feed. The results of this test

showed that no significant upgrading of manganese was obtained under the test conditions. For the test the ore was ground to 100% minus 35 mesh and no doubt at this size inadequate liberation of the minerals was obtained.

## DISCUSSION

A study of the literature pertaining to the treatment of manganese ores showed that in only a limited number of cases can low grade ores be beneficiated successfully. The main difficulties are connected with the intimate and complex association of the minerals present, the tendency for the friable and soft earthy constituents to slime, and the very close physical and chemical properties of the manganese and iron oxides which are often the main constituents of these ores.

Mineragraphic and hand specimen examination of samples from the Adams No. 4 mine, Viti Levu, Fiji, indicated that the ore would present most of the usual problems associated with the upgrading of complex manganese ores. The ore although containing some relatively coarse manganese oxides also contained complex associations of manganese and iron oxides with quartz, and the soft earthy components, wad, limonite, and hematite. From this preliminary examination it was concluded that upgrading of the ore to meet market specifications with recovery of perhaps 50% of the manganese may be possible, using gravity and/or flotation methods of concentration.

The test work conducted, however, showed that this was not possible although by combined jigging and tabling 32.7% of the manganese was recovered in a concentrate assaying 38.2% manganese. This recovery could be increased to 46.2% by including the manganese reporting in middling products. Treatment of the ore by sink float at a specific gravity of 2.80 gave an unsatisfactory separation.

Both froth and table flotation were less successful than gravity concentration and after cleaning a concentrate grade of only 31.9% manganese was obtained. Recovery of manganese at this grade was very low. Although the gravity concentration results could be considered close to the best obtainable from the ore there is a possibility of improving considerably on the flotation results reported, particularly if reagent combinations selective between iron and manganese oxides could be developed. These however have not been reported. The other factors contributing to the unsatisfactory flotation results are the intimate association of minerals and the tendency of many of the minerals to slime on grinding. It is probably for this reason that there is no significant improvement in flotation results as the degree of grinding is increased. Finer grinding, although improving liberation of constituent minerals, would produce a greater proportion of slimes and fine material which would be mechanically carried over in froth products or report in the tailings as slime coatings or particles too fine to recover.

If the slime-forming constituents of the ore were manganese minerals only, upgrading could have been achieved by sizing. Unfortunately both the iron and manganese minerals in the ore are soft and friable and no advantage

could be taken of differences in grinding characteristics of the ore components. Table 8 records the manganese content of various size fractions of the crushed ore and shows that upgrading of the ore by sizing or classification would not be possible.

TABLE 8—Manganese Distribution in Various Size Fractions of Ore Crushed to Minus  $\frac{1}{2}$  in.

| Size Fraction                          | Assay %Mn |
|----------------------------------------|-----------|
| $-\frac{1}{2}$ in. + $\frac{1}{8}$ in. | 19.3      |
| $-\frac{1}{8}$ in. + 10 mesh           | 20.5      |
| -10 + 20 mesh                          | 20.8      |
| -20 + 35 mesh                          | 21.7      |
| -35 mesh                               | 22.3      |
| Slime                                  | 20.1      |

Magnetic concentration after roasting was not investigated as this method, although perhaps providing the only possible method of separating the iron and manganese oxides, was not considered to be a suitable one. It could, however, become a useful method of upgrading gravity or flotation concentrates to meet market specifications and to lower their iron content.

It may be concluded from this investigation that the ore from the Adams No. 4 mine is an extremely difficult one to beneficiate and that no simple method of processing would yield a marketable manganese concentrate with an acceptable recovery of the contained manganese. The development of flotation conditions giving selectivity between iron and manganese oxides would assist in the treatment of the ore, but the complexity of the mineral association and the friability of many of the constituents may still prevent satisfactory metallurgical results being obtained.

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# STRATIGRAPHY OF POKENO DISTRICT, AUCKLAND

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## Summary

The Te Kuiti Group is represented by small fault-involved blocks of Waikato Coal Measures and Mangakotuku Siltstone, and by good outcrops of Whaingaroa Siltstone (Whaingaroan to Duntroonian). An extension, geographically, of the application of "Waitemata Group", allows the term Waikawau Sandstone to be used for an Otaian basal calcareous sandstone formation. It is overlain by the Otaian Mercer Beds which comprise calcareous siltstones and loose brown sandstones. The Plio-Pleistocene Puketoka Formation was derived from rhyolitic and andesitic rocks, but includes sub-aerial fragments from the local Bombay Basalts which were then erupting contemporaneously, and which are now represented by high-level tuffs and rarer flows which lack an obvious source. The younger Franklin Basalts are interbedded with pumiceous clays of Castlecliffian or Hawera age (Pokeno Clay), and can be traced to obvious cones.

There is no information available as to whether a workable coal seam exists in the Pokeno District, but if one does, there seems no possibility of its being closer to the surface than 1,000–1,500 ft deep.

## INTRODUCTION, PREVIOUS LITERATURE, AND ACKNOWLEDGMENTS

Pokeno township, 35 miles south of Auckland, is situated at the southern foot of the Bombay Hills, alongside both the Great South Road and the Main Trunk Railway (Fig. 1). Fyfe (1933) recorded vivianite from

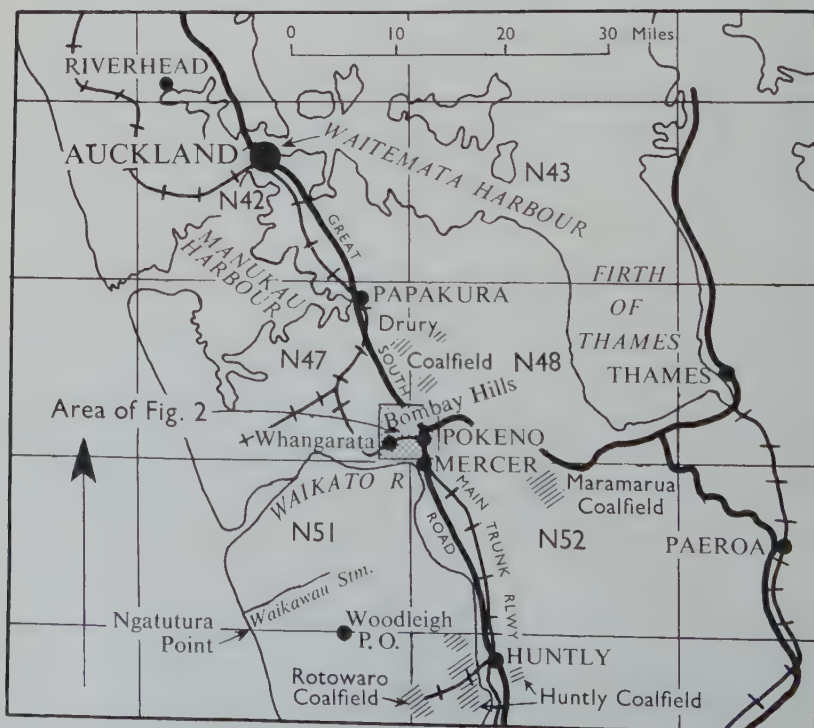
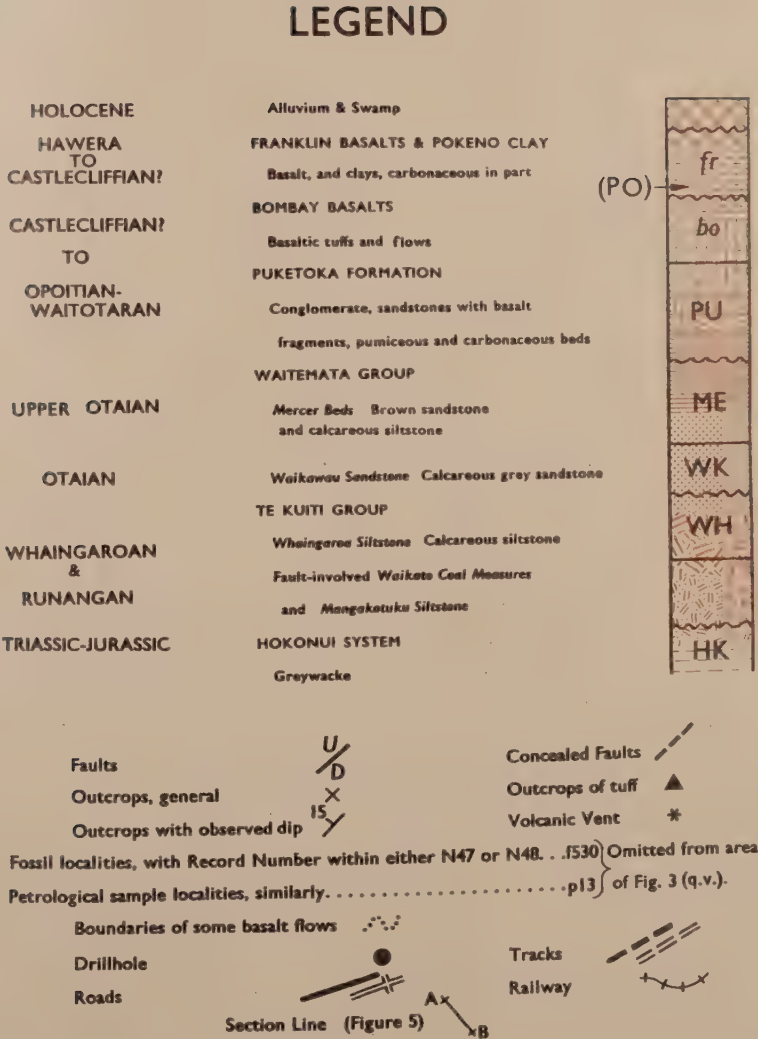


FIG. 1—Locality Map.



Legend for Figs. 2 and 3.

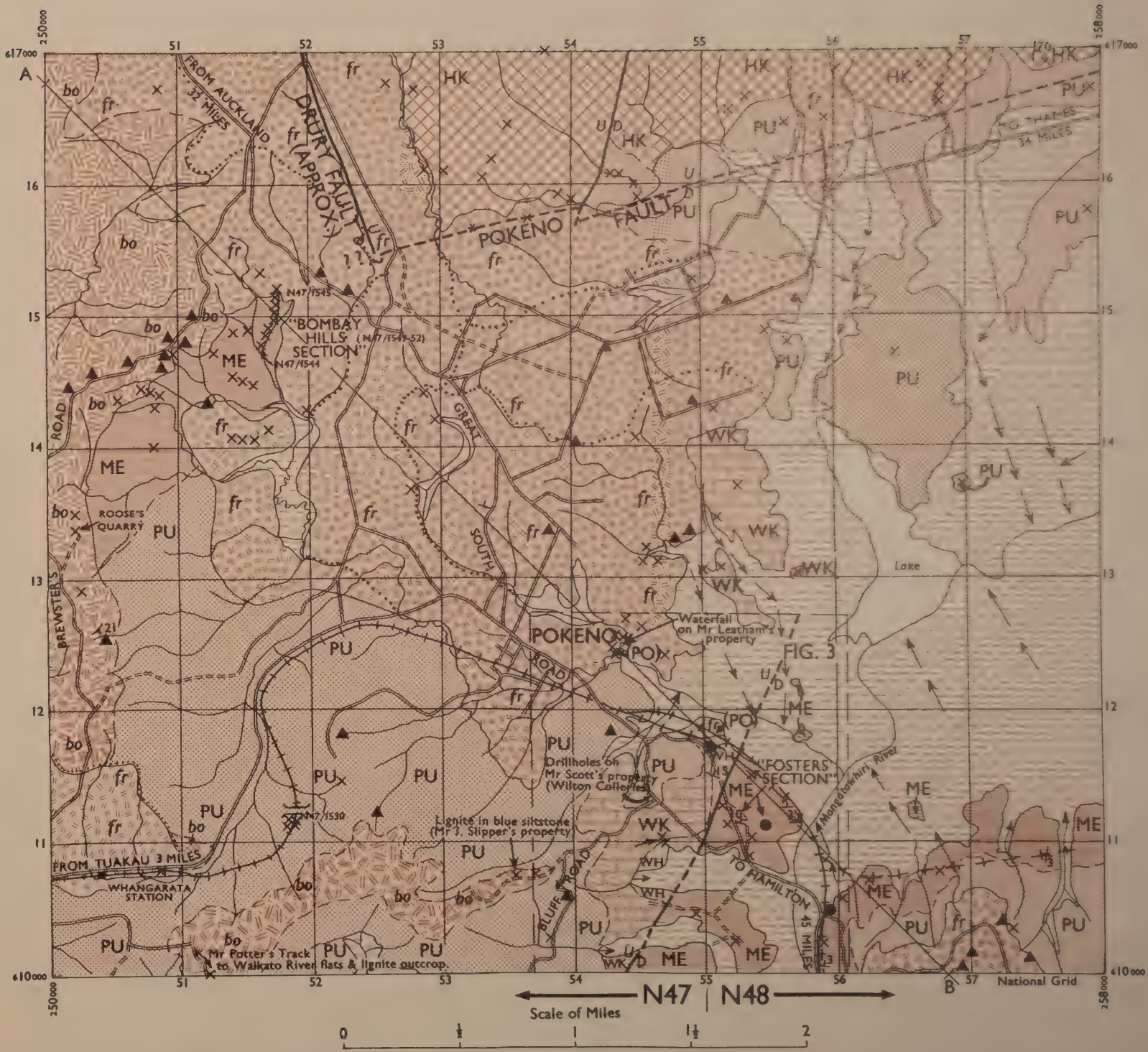


FIG. 2—Geology of the Pokeno District.



there, and the Pokeno District (Figs. 2, 3) was within the area described geologically by Battey (1949). Apart from these publications, however, the district has received scant treatment from geologists since Cox (1882). Bartrum and Branch (1936), Schofield (1958a, 1958b) and Kear (1959) have described the area immediately to the north, and Cox (1877), that immediately to the south. Pokeno is of considerable interest, however, because of the variety of formations that is present in a small area.

Cox (1882, opp. pp. 33–35) not only presented a geological map, but also recorded the log of a drillhole (now numbered 5,000) put down to 540 ft on Mr Hunt's property at Mercer. The drillsite was evidently close to the Kellyville Road level crossing (Fig. 3). Interpretation of the log is uncertain in parts, and the suggested correlation that is implicit in the cross section (Fig. 4) and stratigraphic column (Fig. 5), may be in error in placing the top of the Whaingaroa Siltstone 112 ft too high.

The author gratefully acknowledges that the microfaunal and microfloral ages quoted in this paper were determined by Mr N. de B. Hornibrook and Dr R. A. Couper respectively; the macrofossils were identified by Dr C. A. Fleming and Miss H. Leed; Dr J. J. Reed examined certain rocks petrographically; and the coal samples were analysed by the Coal Section, Dominion Laboratory, Lower Hutt.

## STRATIGRAPHY

Table 1 summarises the stratigraphy of the Pokeno District, and indicates the lithologies of the several formations in some detail. Information regarding the Tertiary rocks was gleaned largely from "Bombay Hills", "Pughs", "Pokeno South Cutting", and "Fosters" sections. These are illustrated in Fig. 5, where locality details are given, and Hunt's drillhole column is compared. Lithologic data presented in Table 1 and Fig. 5 are not necessarily repeated in the text.

### HOKONUI SYSTEM

Pokeno Fault throws up Hokonui jointed, indurated, unfossiliferous, coarse sandstones and siltstones on its northern side (Fig. 2). These rocks form a prominent range of hills which rise 500–1,000 ft above the low, gently rolling land on which Pokeno township has been established.

### TE KUITI GROUP

(Kear and Schofield, 1959; after Henderson and Ongley, 1923)

*Waikato Coal Measures* (Kear and Schofield, 1959; after Hutton, 1867)

*Mangakotuku Siltstone* (Kear and Schofield, 1959)

#### *Description*

The Waikato Coal Measures are not exposed at Pokeno apart from small blocks which, along with Mangakotuku Siltstone are complexly involved in Pokeno Fault (Battey, 1949, p. 435; Schofield, 1958b, Fig. 1b). Coal pebbles, thought to have been derived from the Waikato Coal Measures, are present within Otaian sandstones in "Pokeno South Cutting". They are commonly  $\frac{1}{2}$ –4 in. in length, but larger ones have been reported locally.

TABLE 1

|                               |                                                                                                                                                    | Ft    |
|-------------------------------|----------------------------------------------------------------------------------------------------------------------------------------------------|-------|
| Holocene                      | Alluvium and swamp deposits                                                                                                                        |       |
|                               | <i>Erosional Interval</i>                                                                                                                          |       |
| Hawera to Castlecliffian?     | POKENO CLAY AND FRANKLIN BASALTS                                                                                                                   |       |
|                               | Clays, sandy or carbonaceous in part .....                                                                                                         | 30+   |
|                               | Contemporaneous basalt flows from recognisable cones .....                                                                                         | 250   |
|                               | <i>Erosional Interval</i>                                                                                                                          |       |
| Castlecliffian? to Waitotaran | PUKETOKA FORMATION AND BOMBAY BASALTS                                                                                                              |       |
|                               | "Greywacke"-quartz-chert conglomerates .....                                                                                                       | 250   |
|                               | Basaltic tuff, rarer flows, alluvial sandstones .....                                                                                              | 2100  |
|                               | Pumiceous, rhyolitic and andesitic sediments, containing locally erupted subaerial basaltic fragments; rare carbonaceous beds .....                | 2250  |
|                               | <i>Unconformity</i>                                                                                                                                |       |
| Upper Otaian                  | WAITEMATA GROUP                                                                                                                                    |       |
|                               | <i>Mercer Beds</i>                                                                                                                                 |       |
|                               | Brown, poorly consolidated, non-calcareous medium sandstone, with widely spaced siltstone pebble beds, and thinner grey calcareous siltstone ..... | 180+  |
| Otaian                        | <i>Contact Uncertain</i>                                                                                                                           |       |
|                               | Light grey, calcareous siltstone, frequently massive, but including sandy and some tuffaceous beds .....                                           | 85+   |
|                               | <i>Contact Uncertain</i>                                                                                                                           |       |
| Otaian                        | <i>Waikawau Sandstone</i>                                                                                                                          |       |
|                               | Grey, calcareous sandstone, poorly bedded, with pebble bed (including coal) 30 ft up .....                                                         | 200+  |
|                               | Greensand .....                                                                                                                                    | 5     |
|                               | <i>Unconformity</i>                                                                                                                                |       |
| Whaingaroan                   | TE KUITI GROUP                                                                                                                                     |       |
|                               | <i>Whaingaroa Siltstone</i>                                                                                                                        |       |
| Whaingaroan to Runangan       | Light-grey, massive very calcareous siltstone .....                                                                                                | 140+  |
|                               | <i>Mangakotuku Siltstone</i> }                                                                                                                     |       |
|                               | <i>Waikato Coal Measures</i> }                                                                                                                     |       |
|                               | Apart from small areas involved in Pokeno Fault, represented only by coal pebbles in Waikawau Sandstone .....                                      | —     |
|                               | <i>Regional Unconformity</i>                                                                                                                       |       |
| Jurassic-Triassic             | Hokonui System                                                                                                                                     |       |
|                               | Indurated massive sandstone, and rarer siltstone .....                                                                                             | Thick |

### Age and Correlation

Dr R. A. Couper (pers. comm.) obtained a rich microflora from the coal pebbles (N48/f515; L636), and stated that the following plant microfossils indicate an upper Arnold (Runangan) age, similar to that of the Waikato Coal Measures in the Maramarua Coalfield to the east and at Bombay in the Drury Coalfield to the north.

- Nothofagus matauraensis* Coup. (Arnold to Landon)  
*N. asra* Coup. (Arnold to Southland)  
*Triorites harrisii* Coup. (Arnold to Taranaki)  
*Liliacidites kaitangataensis* Coup. (Mata to Arnold)  
*Dicotetradites clavatus* Coup. (Arnold)

Presumably the pebbles were derived from Waikato Coal Measure seams. Their analyses (a201, a201A) are compared in Table 2 to an average value given by Kear (1959) for the thin and dirty coal seams of the Drury Coalfield, and to a similar figure for the thicker and cleaner seams of Maramarua.

TABLE 2—Proximate Analyses of Coal Samples

| Pokeno Coal Analyses           |              |        |                         | Broad Average Values<br>for<br>Nearby Coalfields |           |
|--------------------------------|--------------|--------|-------------------------|--------------------------------------------------|-----------|
| Material                       | Coal Pebbles |        | Platy Coal<br>Fragments |                                                  |           |
| Field No.<br>(N48)             | a201         | a201A  | a201B                   | Drury<br>(Kear, 1959)                            | Maramarua |
| Lab. No.                       | CS5266       | CS9214 | CS9215                  |                                                  |           |
| Moisture (%)                   | 20.9         | 13.7   | 9.7                     | 18                                               | 20        |
| Volatile Matter (%)            | 36.3         | 39.7   | 44.1                    | 34                                               | 37½       |
| Fixed Carbon (%)               | 41.0         | 41.6   | 38.7                    | 36                                               | 37½       |
| Ash (%)                        | 1.8          | 5.0    | 7.5                     | 12                                               | 5         |
| Sulphur (%)                    | 0.4          | 1.06   | 1.19                    | 1                                                | ¼         |
| Calorific Value<br>(B.t.u./lb) | 9600         | 9690   | 10,540                  | 8900                                             | 9400      |

### *Whaingaroa Siltstone* (Hutton, 1867)

Very calcareous, light grey, massive siltstones, totalling about 50 ft in thickness, are exposed in "Pokeno South Cutting", in the road cuttings immediately to the south, and at "Pugh's" section ½ mile further south (Fig. 3, 5). Samples from these localities (N47/f518-9, N48/f500-3, 505, Fig. 3, 5) contain microfaunas of from Whaingaroan to Duntroonian age (Mr N. de B. Hornibrook, pers. comm.). The Duntroonian age implies that only the upper part of the formation is exposed, because, of the 664 ft of Whaingaroa Siltstone that was penetrated in drillhole 4996 at Mercer (Kear and Schofield, 1959, fig. 2), only the top 48 ft at most was as young as Duntroonian.

### WAITEMATA GROUP

(Hochstetter, 1864)

#### *Nomenclature*

The Waitemata Group, at present considered to extend geographically as far south as Mercer (Dr R. N. Brothers, in Fleming, 1959, p. 458; Kear, 1959), consists typically of interbedded marine sandstones and marls (Hochstetter, 1864). Towards its base, the beds are coarser, notably more calcareous, and locally include the Otaian Papakura Limestone which rests unconformably upon Te Kuiti beds. The Waitemata Group is thus





The importance of the above proposal, in the Pokeno area, is that the term "Waikawau" is then available as a formation name. At the type locality at Waikawau Stream mouth (Fig. 1), the beds consist of calcareous grey sandstones which rest unconformably on Te Kuiti beds, and which are of Otaian age (Mr N. de B. Hornibrook, in Fleming, 1959, p. 293). (The basal "Cardita Beds", which are 3 ft thick and intervene between undoubted Te Kuiti and Waikawau strata, are interesting and merit further study, but, being of very small lateral extent, they do not affect the present issue.) The term "Waikawau Sandstone" may thus be applied to a near-basal grey calcareous sandstone formation of the Waitemata Group, which is known to be of Otaian age at its type locality. Where it does not rest directly upon pre-Waitemata rocks, either Papakura Limestone or basal fossiliferous "Cardita Beds" may intervene.

The adoption of the name "Waikawau Sandstone" for this near-basal Waitemata formation in the South Auckland area, allows the term "Mercer Beds" to be restricted in its application.

"Mercer Beds" was introduced by Cox, in 1877. He recorded that this formation overlay the *Leda* Marls (Whaingaroa Siltstone), and comprised (pp. 14-5) "a series of light blue marls and loose brown sands, in which fossils are very scarce, but which appear to be equivalents of the Waitemata Beds, as developed towards Riverhead, in the Auckland Harbour. These beds are well exposed in the railway cuttings near Mercer [immediately south of the present district] and they are also seen at Foote's coal mine [Maramarua Coalfield], in both cases the *Leda* marls appearing at the base of the series, and they must, I am inclined to think, be considered as the higher beds of the *Leda* marls, as developed towards the centre of the basin". In a later paper Cox admitted (1882, p. 36) that an unconformity must exist between the Mercer beds and the *Leda* marls.

In the Maramarua Coalfield Cox's "light blue marls and loose brown sands" are underlain by basal Waitemata calcareous and concretionary sandstone of Otaian age. A similar basal calcareous sandstone is present at Pokeno, where the terms Waikawau Sandstone and Mercer Beds can thus be conveniently used. Further subdivision of the latter will undoubtedly be possible in areas where the sequence is more completely exposed.

### *Waikawau Sandstone* (Henderson and Grange, 1926)

#### *Description*

Grey or blue-grey massive sandstone, which is calcareous when unweathered, overlies the Whaingaroa Siltstone at Pokeno South Cutting, in road cuttings immediately to the south, and at Pugh's Section (Fig. 3, 5). A basal greensand is present at the first and third localities, and over 200 ft of beds are represented altogether. An unconformity below them is implied (apart from the absence of the Waitakian stage) by the presence of Waikato coal pebbles, up to 4 in. long, in a band 30 ft up from the base (Fig. 5), although no discordance is obvious. In addition to round pebbles, slightly smaller platy fragments of bright coal are present. They may also have been derived from Waikato coal seams, or they may be coalified wood fragments of Otaian age.

The upper beds in Pokeno South Cutting are mostly weathered and therefore non-calcareous. All beds are weathered in the road outcrop immediately south of the railway cutting, where grey and yellow fine sandstones with siltstone laminae are exposed. The Waikawau Sandstone was found to be a uniformly calcareous, light blue-grey, medium sandstone, with some glauconitic horizons in drillhole 4997 (Fig. 3, 5) which was put down in 1952 by the N.Z. Geological Survey's rig (Mr P. J. Sweeny, driller).

### *Age and Correlation*

Otaian Foraminifera, with *Ebrenbergina* and *Globigerina dissimilis*, have been found in microfaunal samples (Fig. 5) from the Waikawau Sandstone (Mr N. de B. Hornibrook, pers. comm.).

Macrofossils are uncommon. Miss H. Leed, formerly of the N.Z. Geological Survey (pers. comm.), identified the long ranging *Ctenamussium vafer* in the only field collection made — a number of shell fragments from near the base of the formation (N48/f504, Fig. 5). Dr C. A. Fleming (pers. comm.) noted a crab chela and a few Polychaete (?) tubes in cores from drillhole 4997 (sample N48/f522).

Correlatives of the Waikawau Sandstone at Waikawau and Maramarua have been noted above in the discussion of the nomenclature of the Waitemata Group. The near-basal Waitemata calcareous sandstones and conglomerates of the Drury Coalfield (Kear, 1959), should be considered as a coarse facies of the Waikawau Sandstone, now that the term "Mercer Beds" is restricted to slightly younger strata.

### *Mercer Beds (Cox, 1877)*

#### *Description*

The present paper continues Cox's usage (1877, pp. 14–5, and see above) of "Mercer Beds" for "light blue marls and loose brown sands" of the Mercer-Pokeno-Maramarua region. The former are well exposed as the "Bombay Hills Section" inlier (Fig. 2, 5), where nearly 100 ft of calcareous siltstones include sandstone and some tuffaceous beds at irregular intervals.

Calcareous siltstones are also exposed in Great South Road cuttings near Mr Foster's property (Fig. 3, 5), and were encountered at a depth of 132 ft in his water drillhole (4998) nearby (Fig. 3, 5). Brown, poorly consolidated, non-calcareous, medium sandstones ("loose brown sands" of the driller's log) intervene between these two siltstones, and are well exposed in road and railway cuttings between Foster's and Mercer (Fig. 2). These sandstones include widely spaced non-calcareous siltstone beds up to 1 in. thick, and a few scattered siltstone pebbles and boulders.

Dr J. J. Reed (pers. comm.) has identified abundant altered acid volcanic glass and occasional tridymite in samples of the siltstone collected from cuttings near "Foster's Section" (N48/p13 and 15, from the thick upper siltstone; N48/p14 from a thin siltstone bed within the sandstone; Fig. 3, 5).

*Stratigraphic Sequence, Age and Correlation*

The brown sandstones and less common siltstones of Foster's section (Fig. 5) are considered to belong to the Waitemata rather than the Te Kuiti Group because they are so poorly calcareous (see Kear and Schofield, 1959, p. 708). Their close proximity to Pokeno South Cutting, where Waikawau Sandstone is the basal Waitemata formation, implies that they themselves are post-Waikawau. The relative stratigraphic position of the calcareous siltstones of the Bombay Hills Section is less certain, but sequences in which calcareous sandstones pass directly up into relatively massive calcareous siltstones are sufficiently common for the simple solution to be accepted tentatively that they are post-Waikawau.

The above sequence is supported by microfaunal evidence. The lowest and highest of several samples (Fig. 5) from the Bombay Hills Section gave the best faunas, and these were identified as "Waitakian to Pareora, probably Otaian" and "Otaian" respectively (Mr N. de B. Hornibrook, pers. comm.). An Otaian age is adopted for these rocks. Of the beds exposed in Foster's Section, no fossils have been found in the sandstones, but the calcareous siltstones contain Foraminifera. The late Dr H. J. Finlay determined a Waitakian age for an early sample (No. 9 in Battey, 1949, p. 455) from the Great South Road locality N48/f510 (Fig. 3, 5). Subsequent micropaleontological investigation of siltstones in Mercer district including this fauna and that from a siltstone 150 ft lower stratigraphically in Foster's drillhole (N48/f520, Fig. 5), suggested that they were not far below the zone of *Globorotalia miozea* and a Hutchinsonian age was adopted for them (Hornibrook in Fleming, 1959, p. 141). An upper Otaian age now seems more likely as *Globorotalia miozea* has recently been found in the type Hutchinsonian and in the Southburn Sands, overlying the type Otaian, indicating that the Hutchinsonian is within the zone of *miozea* (sensu lato) and not below it as previously believed (Mr N. de B. Hornibrook, pers. comm.).

Very similar interbedded thick calcareous siltstones and poorly consolidated sandstones are well exposed in the Tuakau Bridge - Onewhero area (Battey, 1949, p. 434).

*Puketoka Formation* (Battey, 1949)

and

*Bombay Basalts* (Schofield, 1958b)

*Puketoka Formation*

The Puketoka Formation consists typically of thick pumiceous siltstones overlain by conglomerates (Battey, 1949, pp. 438-42). Both these contrasting lithologies are present at Pokeno, but some of the pumiceous beds there are probably older than those at the type Puketoka area. Minor carbonaceous beds have been dated at two localities near Pokeno.

Immediately east of the Great South Road concrete bridge (Fig. 3), a railway cutting exposes white carbonaceous siltstone overlying 35 ft of soft purple siltstone and quartz sandstone. These beds are only slightly pumi-

ceous, and are considered to contain a microflora (N47/f524, L537) of Waitotaran age (Couper, 1960), which includes the following plant microfossils.

*Nothofagus cranwellae* Coup.

*Polypodioidites inanagabuensis* Coup.

*Proteacidites minimus* Coup.

In a railway cutting 60 chains east of Whangarata Station (Fig. 2), 25 ft of massive pumiceous siltstone and sandstone, very like the type Puketoka, overlies 12 ft of fine grey sandstone with a sharp contact intervening. The latter bed rests on  $2\frac{1}{2}$  ft of woody lignite. Dr R. A. Couper states (pers. comm.) that the microflora from the lignite (N47/f530, L486) includes no extinct species and is therefore post-lower Nukumaruan in age.

Beds that may be intermediate in age between those at the two above localities, are exposed in the general area between them, often as bluffs or other prominent outcrops. They are typically well-bedded sandstones or conglomerates, and contain varying amounts of basalt fragments of up to cobble size. At least some of these fragments are the subaerial products of contemporaneous volcanism, because dints in the underlying bedding are shown in bluff outcrops west of Pokeno South Cutting (N47/543118, Fig. 3). The erosion of the bluffs pre-dates the Franklin Basalt flow immediately to the north, and hence the fragments within the Puketoka Formation are probably from earlier Bombay Basalt eruptions (Schofield, 1958b).

Dr J. J. Reed has examined a sample (N47/p505, P20274, Fig. 3) of the sandstones petrographically, and reports (pers. comm.) that they are derived from both rhyolitic and andesitic sources. "Thus the common occurrence of pumiceous glass, quartz, orthoclase and altered biotite indicate clearly a rhyolitic origin, and the less plentiful hornblende, hypersthene, augite, and brown glass an andesitic source". Two very different sources of these sediments are therefore indicated. Petrography shows that the bulk of the sandstones were derived from a rhyolitic-andesitic source such as Rotorua-Taupo or Coromandel, while field evidence shows that a fair amount of locally-derived basalt was added during deposition.

Half a mile south-east of Whangarata railway station, a bulldozed track leads down southwards from the tuff-covered hills to the Waikato River flats (Fig. 2 shows the upper part of the track with tuff outcrops), and exposes 300 ft of brown, poorly consolidated medium sandstone, with minor quartz grit beds. Rare conglomerate lenses include rounded siltstone pebbles that appear likely, lithologically, to have been derived from Mercer siltstones. If this be true, then the sandstones have probably been mapped correctly as Puketoka Formation on Fig. 2, although their lithologic resemblance to the Mercer sandstones makes this uncertain.

The upper Puketoka conglomerates are exposed at Pokeno South Cutting and in the road cutting immediately to the south. The pebbles are commonly  $\frac{1}{2}$ -2 in. across, and are so thoroughly weathered that identification is uncertain. Most undoubtedly were derived from Mesozoic indurated sandstone, but rhyolite, quartz, and chert fragments are rarely present. Some of the very weathered sandstone pebbles could have been derived from the Waikawau Sandstone which underlies the conglomerate unconformably at that locality.

### *Bombay Basalts*

Schofield's criteria (1958b, pp. 546-7) for differentiating the Bombay from the younger Franklin Basalts depend wholly upon the relative states of preservation. The Bombay Basalts were stated to be more deeply weathered, to have no readily recognisable eruptive centres, to be exposed most frequently as coarse tuffs which are not a recognisable part of a tuff ring, and to underlie a plain at Bombay, 540-60 ft above sea-level, which is covered by volcanic ash.

By these criteria the basaltic rocks along Brewster's Road and at the crest line of the hills south of the Main Trunk Line (Fig. 2) may be referred to the Bombay Basalts. They are deeply weathered, they have no obvious source, they consist for the greater part of tuff, and they are eroded to the form of "razorback" ridges (Battey, 1949, p. 445) and hilltop remnants which rise to heights of from 300 to nearly 600 ft. They rest on Puketoka sandstones and conglomerates containing subaerial basalt fragments which are thought to have been derived from the Bombay Basalts. The contact between these two formations is therefore indefinite, and one formation could grade into the other, or could appear to do so, where outcrops were poor. In the good track exposures south-east of Whangarata Station (see above) the contact is sharp, however.

The basalts are well exposed in Roose's Quarry, Brewster's Road (N47/502134). They range from hard and dense to very scoriaceous rocks, and include white zeolites in vugs, and olivine nodules.

### *Age*

The age of microfloral samples from the pumiceous beds of the Puketoka Formation ranges from "Waitotaran" to "younger than lower Nukumaruan" (see above). Intraformation erosional intervals could well be present, and continuous sedimentation did not necessarily occur over this range. The overlying Pokeno Clay has been dated as Castlecliffian, but might be younger (see below).

The age range of the Puketoka and Bombay formations is therefore known to be at least as wide as Waitotaran to Nukumaruan. This is in keeping with Schofield's (1958b, p. 547) suggested correlation of the Bombay with the Ngatutura Volcanics of upper Waitotaran to lower Nukumaruan age (Kear, 1957, p. 837). The total age range of the formations may reach up to the Castlecliffian or even to the Hawera.

*Pokeno Clay* (New Formation)  
and  
*Franklin Basalts* (Schofield, 1958b)

### *Pokeno Formation*

*Description:* The Pokeno Clay is named after Pokeno Township. Its type locality is at the northern cutting of the south-bound Main Trunk railway track, 35 ch east of the Great South Road overbridge (grid reference

N47/549118, Fig. 3). This locality is at the northern end of "Pokeno South Cutting", and the following sequence is exposed there:

|                                                                                                                                                                      | Ft |
|----------------------------------------------------------------------------------------------------------------------------------------------------------------------|----|
| Pink and white pumiceous clays, during the deposition of which basalt pillow-like blocks have been thrust into the clay which was squeezed between pillows and baked | 20 |
| Very soft white clay                                                                                                                                                 | 5  |
| Carbonaceous mudstone with leaves (sample N47/f514)                                                                                                                  | 5  |

On the southern side of the track, 5 chains east of this locality, the basal carbonaceous mudstone, containing leaves and seeds, is about 10 ft thick, and overlies Puketoka conglomerate.

Fyfe (1933) described another sequence of the Pokeno Clay at a waterfall on Mr C. J. Leatham's property (Fig. 3). Beneath the basalt flow, the original soil is now represented by baked mudstone prisms,  $\frac{1}{2}$ –1 in. across and 2–4 in. long, which grade down into blue soft sandy mudstone. Interbedded with the latter is a 2–3 in. bed of tuffaceous sand, which contains feldspar, quartz, glass, hornblende, and hypersthene grains, and both it and the mudstone contain vivianite (Fyfe, 1933).

*Age:* Couper and McQueen (1954, p. 403) examined plant fossils from the lowest bed of the type locality (sample N47/f514, L227). In the absence of extinct microfossils, they proposed a probable Castlecliffian age on the basis of a leaf *Beilschmiedia ovata* Oliver, that was "not known from floras younger than the Waipaoa flora" which was described by Oliver in 1928 (see also McQueen, 1954). The Pokeno Clay appears to fill relatively young valleys at low levels, however, and physiographic considerations suggest a Hawera rather than a Castlecliffian age.

### Franklin Basalts

*Description:* A basaltic cone, lacking a crater, and considerably eroded on its northern side, has erupted on the line of Pokeno Fault at a point  $\frac{1}{2}$  mile north of the Thames road junction with the Great South Road (N47/533157, Fig. 2). The southern slopes are less eroded, and appear to grade into the slightly rolling country to the south which is largely underlain by basaltic ash. Basalt has been encountered in drillholes there (Battey, 1949, p. 445), and is exposed rarely at the base of deep road cuttings or stream valleys.

Using the criteria of the presence of a cone and the low level of the flow, these occurrences have been mapped as Franklin Basalts, along with a much less eroded and therefore younger flow that has descended southwards from a cone immediately north of the area of Fig. 2. The Great South Road is now formed upon it. Within the immediate area of Pokeno township this younger flow is covered to a greater or lesser extent by unmapped alluvium.

One of the most interesting areas of Franklin Basalt extends northwards from Pokeno South Cutting. Here, at the type locality of the Pokeno Clay, the basalt is comprised solely of fresh sub-rounded blocks 6 in. to 5 ft across, which are stacked up to 20 ft high. Their corners and edges are rounded, and their surfaces are smoothly dented where one is almost in contact with the next (Fig. 6). Each has a finer grained selvedge,  $\frac{1}{4}$ – $\frac{1}{2}$  in.



FIG. 6—Pillow-like blocks of Franklin Basalt, at northern end of Pokeno South cutting (N47/549118).

in thickness, in which olivine crystals and a meshwork of fine feldspar laths up to  $\frac{1}{2}$  mm long are present in a glassy matrix. This contrasts with the holocrystalline interior of the blocks where prominent feldspar and olivine crystals are  $\frac{1}{2}$ –2 mm long. The surrounding Pokeno clays have been squeezed thinly and hardened between the blocks.

The blocks show several similarities to marine basalt pillows, and may be described as "pillow-like". They are essentially blocky lava that flowed

into a small lake with a clay bed. Nearby lava is not blocky, and it is presumed that the flow must have broken up on meeting the cold water and sediment. This shattering may have been assisted by the lava's falling over a low bank into the lake.

Many road cuttings expose red-brown to ochre-brown weathered ash which contains an increasing number of basaltic bombs downwards. The thickness is variable, but is frequently greater than the height of the cutting; it shows every indication of increasing towards the Bombay Hills, where it reaches over 20 ft. and is commonly between 5 and 15 ft around the base of the Hills.

*Petrography:* Dr J. J. Reed (pers. comm.) has supplied the following petrographic notes.

"Basalt samples were examined from Pokeno South Cutting (N47/p4; P12309, 12146, Fig. 3), and from the waterfall on Mr C. J. Leatham's property (N47p6; P12305-8, Fig. 3). The lavas from the Pokeno South Cutting contain plentiful olivine phenocrysts (up to 1.5 mm in length), smaller violet-coloured augite prisms (0.1-0.5 mm), and labradorite laths (0.6 mm) arranged in intergranular texture. Iron ore, as widely scattered granules 0.1 to 0.2 mm in width, and as skeletal crystals in the sparse matrix, completes the assemblage. The olivine crystals are generally fresh but some are altered to chlorite around the rims, and others are completely replaced by red iddingsitic material. Chloritic pools are not uncommon. Zeolites, replacing plagioclase, are seen in both sections, particularly P12309. The rocks from Leatham's waterfall are similar basalts together with a tachylitic type containing abundant brown glass (P12305). Fibrous zeolite is plentiful in P12307-8, and to a less extent in P12306.

"The major petrographic problem is whether the basalts are basanites as asserted by Marshall (1908, p. 96) although later workers (Henderson and Grange, 1926, pp. 69-70; Battey, 1949, pp. 446-7) could not find any evidence of feldspathoids. Marshall based his identification on gelatinisation and staining, as well as on cubes of salt obtained when the solution derived from treatment of the rock-powder with hydrochloric acid is evaporated. These tests have little diagnostic value where zeolites are prevalent as is the case with the rocks examined. Further the fine grained pilotaxitic basalt from Mercer analysed by Henderson and Grange (1926, p. 71, no. 18) contains a plentiful zeolite (P17458) and is undoubtedly the explanation for the presence of 8.24 per cent nephelite in the normative calculation. Zeolites are also widespread in the other analysed rocks from Ngatutura (P18886, Fig. 1) and near Woodleigh Post Office (P17454, 18885, Fig. 1). The lavas must be classified as basalts until the presence of nephelite is definitely proven".

*Age:* The interbedding with Pokeno Clay shows that the Franklin Basalts are Castlecliffian or Hawera in age. Close to Pokeno township, the surface of near-flat basalt flows is 70 ft and less above sea level, and streams have cut down into the flows by amounts ranging from 10 to 40 ft. Thus, although pre-Holocene, the formation post-dates the Tyrrhenian sea level (110 ft) as Schofield (1958b, p. 546) pointed out. Its relation to Monastirian levels is less certain — some flows appear younger than the higher

Monastirian levels, but the older ones could pre-date the 40 to 80 ft level as Schofield found farther north-west.

### HOLOCENE

Holocene deposits comprise alluvium and swamp of the Waikato and Mangatawhiri valleys. Depressions in the constructional surfaces of basalt flows have often been filled with alluvium by tributary streams, but these areas have generally been omitted from the maps.

### STRUCTURE

Pokeno Fault dominates the structure of the Pokeno District, and at least one volcanic vent is located on it. The fault strikes  $075^{\circ}$ , and is down-thrown to the south. No observational evidence as to its nature was forthcoming, and the amount of its throw is uncertain. Equally uncertain is its extension westwards beyond the point at which it would meet a southward continuation of Drury Fault (Fig. 2). Only a regional study, beyond the confines of the Pokeno District, would elucidate what extensions these faults may have to the west and south. A less important fault, between Foster's and Pokeno South Cutting sections, is poorly located, but may strike about north-north-west. It is downthrown to the south-east by possibly 600 ft.

Only one reliable dip measurement was made in the Mesozoic rocks –  $70^{\circ}$  eastwards.

The pre-Pliocene Tertiary beds appear to dip regionally north or north-west at up to  $30^{\circ}$ . The lowest dips have been recorded in the Mercer Beds ( $3^{\circ}$  to horizontal). This fact, coupled with the incoming of tuffaceous horizons and the presence of siltstone pebbles and boulders in the sandstones, suggests that the eventual onset of the Kaikoura Orogeny was already being heralded at the time of Mercer deposition.

Pliocene and younger beds have not been tilted perceptibly.

### COAL POSSIBILITIES

Rumours of the presence of coal are common locally. When investigated, none of them proved to be of any economic significance, and all were related to one of the following:

- (1) Coal pebbles in Waikawau Sandstone, similar to those noted above from "Pokeno South Cutting", although much larger pebbles have been found (Messrs Cronin and G. Little, pers. comm.):
- (2) Unworkably thin lignite or peat beds in Puketoka or younger formations, such as occur in railway cuttings between Whangarata and Pokeno (N47/519119), on Mr J. Slipper's property on Bluff Road (N47/535108), and at river flat level on Mr Potter's Farm (N51/516098) – see Fig. 2 for all localities; or

- (3) To drillholes on Mr Scott's property, Bluff Road (N47/545115, Fig. 2), where Wilton Collieries Ltd prospected, but found no coal (Mr T. Geddes, ex-Manager, pers. comm.).

The order of total depth to a hypothetical coal seam at Pokeno can be estimated from the evidence of drillhole 4996 at Mercer, and the sequence in Maramarua Coalfield (Kear and Schofield, 1959). Apart from possible small blocks involved in Pokeno Fault, the shallowest coal should be found below the outcrops of Whaingaroa Siltstone which are considered to be near the top of that formation (see above). The Whaingaroa Siltstone was 664 ft thick at Mercer, and was underlain by 298 ft plus of Mangakotuku Siltstone. At Maramarua, these formations are 250 ft plus and 250–400 ft thick respectively, with a further 150 to 250 ft of coal measures above the coal seam. Hence at Pokeno a seam would probably be at least 1,000–1,500 ft deep. There is of course no certainty that a seam as such would in fact exist, and no knowledge of its possible thickness.

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## THE PETROLOGY OF THE AUCKLAND BASALTS

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### Summary

The rocks of the Auckland volcanoes (late-Pleistocene and Recent) include the following types: olivine basalts; augite-rich picrite basalts; nepheline basanite. Less common varieties described are: basalts with noteworthy biotite; amphibole (cummingtonite) basalt, and rutile-bearing scoriaceous basalts associated with dykes intruding scoria cones and spatter cones. Ultrabasic nodules, interpreted as fragments of border facies crystallite, occur in tuff rings surrounding phreatic craters and supply xenolithic inclusions to minor flows associated with adjacent vents.

### INTRODUCTION

In a recent paper, Searle (1959) discussed the chemical nature of the magma that supplied the Auckland volcanoes, and showed that the rocks they produced could best be regarded as olivine-rich alkaline basalts. In the present contribution it is proposed to consider the mineralogical and petrographic characteristics of the rocks, on the basis of the examination of several hundreds of thin sections in the petrological collection of the Department of Geology, University of Auckland. Reference in this account is made to particular sections by their serial numbers in that collection. The majority of the sections have been cut from rocks in the various thin flows emanating from the numerous vents scattered over the Auckland field. In most cases it is not known from what position with respect to depth in the flow the samples were obtained. However, examination of sections cut from a number of drill cores taken from different flows, shows that the rocks vary little with depth below the surface. It may be accepted, therefore, that most groups of sections are truly representative of the rock throughout the flows from which they have been cut. Other sections have been cut from bombs, from blocks and scoriae in pyroclastic accumulations, and from irregular dykes intruding into them, and also from tuff bodies.

Consideration of the petrology of xenolithic inclusions frequently observed in the lavas and of other pyrometamorphosed materials encountered during the survey has not been included in this article but has been reserved for a further contribution.

### MODAL ANALYSES

The basalts typically are dense, blue-grey or blue-black, fine-grained rocks with a simple mineralogy. Olivine, clinopyroxene, feldspar and ore (usually magnetite or ilmenite) are constant constituents. Of these, olivine alone occurs as large insets; other phenocrystic minerals are rarely more than

0.6 mm in longest dimension. The groundmass is usually intersertal to intergranular in texture, but occasionally, as in the nepheline-bearing type, or elsewhere where residual liquids have become segregated before solidification, the rock has a pegmatoid or doleritic texture. Very commonly the groundmass is provided by an intersertal-like crystallisation of residual alkali-rich feldspar of low r.i., undulating extinction, and positive figure, optically comparable with the potash oligoclase of Macdonald (1942). In most instances the basalt is notably vesicular only in the upper zones of the flows which vary in thickness from a few feet to as much as 70 ft.

Modal analyses of representative rocks, calculated on mineral counts made with a Swift electric point counter, whilst scanning with a  $\times 30$  objective, are presented in Tables 1 and 2. The pyroxene count, as also that of olivine, includes both phenocrystic and granular individuals; that of feldspar includes both phenocryst and microphenocryst grades and even coarse feldspar of the residue where this was clearly crystalline feldspar. "Intersertal" feldspar with undulating extinction together with glassy mesostasis and all unresolvable material were counted as groundmass. This procedure was followed in order to present a clearer picture of the constitution of rocks in which there is no clearly defined differentiation between phenocryst and microphenocryst and between microphenocryst and residue grades, and in which any arbitrary fixing of limit sizes of these grades would be both artificial and confusing.

In considering the classification on mode of the not dissimilar, although more varied, volcanic rocks of Hawaii, Macdonald (1949) adopted the following criteria:

- (a) Where feldspar (labradorite or bytownite) was more than 35%: and
  - (i) olivine  $> 5\%$ —*olivine basalt*
  - (ii) olivine  $< 5\%$ —*basalt*
- (b) Feldspar  $< 35\%$ —*picrite basalt*
  - (i) mafic minerals entirely or almost entirely olivine—*primitive picrite basalt*.
  - (ii) abundant phenocrysts of augite in addition to numerous olivine phenocrysts—*augite rich picrite basalt*.

Where the average composition of the modal feldspar was andesine or oligoclase the rocks were classified as andesites.

It may be argued (as, for example, Washington, 1923) that the use of modal olivine for the classification of volcanic rocks is unsatisfactory on the grounds that modal olivine is frequently in excess of normative proportions as a result of the early separation of olivine in excess of stoichiometric proportions and of the subsequent reluctance of the system to adjust the stoichiometric balance. Nevertheless, as a distinctive component of the mineral assemblage olivine would appear to be an obvious choice as a diagnostic mineral of rock type. The arbitrary levels of 5% for olivine and 35% for feldspar would appear to be satisfactory bases for classification in the case of the Hawaiian basalts and, for convenience in comparison, may conveniently be retained for like suites in other areas. It will be appreciated, however, that some difficulty in applying these criteria in classification arises both from the measurement of and the meaning to be attached to, "the percentage of feldspar". The phenocrystal grade represents

but a small part of the total feldspar of a rock and if classification were based on the proportion of this alone it would, in fact, result in a classification unduly influenced by textural factors. The total feldspar may be regarded as consisting of phenocrystic feldspar, "intersertal" residual feldspar, the feldspathic components of the cryptocrystalline groundmass and the potential feldspathic constituent of any glassy mesostasis. As noted above, in the present investigation, feldspar of the groundmass, unless clearly plagioclase, is not included in the feldspar count but has been counted as groundmass. Further, it is clear that almost the whole of a glassy or cryptocrystalline groundmass, as counted, would on crystallisation separate as feldspar, seeing that granular pyroxene and ore resolvable by the optic system is accounted for elsewhere. For the purpose of classification therefore the groundmass percentage and the feldspar percentages have been combined and regarded as "total feldspar". Any error so introduced will tend to throw borderline rocks into the basalt rather than the picrite basalt classes. A term such as "average composition of modal feldspar" obviously lacks precise meaning but the chemical analyses presented in a previous article (Searle, 1959) leave no doubt that all the rocks examined in this survey are far too basic to be considered as possible andesites, so that further search for a working definition of the term may well be regarded as unnecessary.

TABLE 1.—Modal Compositions of Auckland Basalts (Percentages by Volume)

(Textures: A = intergranular; B = intersertal; C = hyalopilitic; Peg = pegmatoid.)

|                  | 1    | 2   | 3  | 4       | 5   | 6   | 7   | 8   | 9    | 10  | 11 | 12                                        | 13 | 14  |
|------------------|------|-----|----|---------|-----|-----|-----|-----|------|-----|----|-------------------------------------------|----|-----|
| Olivine          | 16.3 | 20  | 12 | 19      | 19  | 16  | 20  | 19  | 22   | 15  | 13 | 20                                        | 20 | 9   |
| Pyroxene         | 25.5 | 24  | 22 | 31      | 40  | 30  | 31  | 32  | 33   | 36  | 40 | 31                                        | 34 | 43  |
| Feldspar         | 47.8 | 31  | 27 | 17      | 23  | 10  | 25  | 15  | 14   | 12  | 8  | 19                                        | 9  | 3   |
| Ore              | 7.2  | 7   | 16 | 9       | 8   | 13  | 11  | 9   | 10   | 12  | 9  | 12                                        | 10 | 12  |
| Groundmass       | 3.2  | 18  | 23 | 24      | 19  | 31  | 15  | 25  | 26   | 26  | 30 | 18                                        | 27 | 33  |
| Other            |      |     |    |         |     |     |     |     |      |     |    |                                           |    |     |
| Texture          | A-B  | A-B | B  | B       | A-B | B   | A-B | A   | A    | B   | B  | B                                         | A  | B-C |
| "Total Feldspar" | 51   | 49  | 46 | 41      | 42  | 41  | 40  | 40  | 40   | 38  | 38 | 37                                        | 38 | 36  |
|                  | 15   | 16  | 17 | 18      | 19  | 20  | 21  | 22  | 23   | 24  | 25 | 26                                        | 27 | 28  |
| Olivine          | 20   | 16  | 13 | 33      | 20  | 20  | 20  | 20  | 17.7 | 21  | 9  | 6                                         | 3  | 17  |
| Pyroxene         | 39   | 45  | 42 | 32      | 40  | 42  | 49  | 47  | 16.8 | 38  | 45 | 31                                        | 17 | 42  |
| Feldspar         | 7    | 7   | 6  | 18      | 10  | 12  | 9   | 6   | 6.5  | 17  | 10 | 45                                        | 26 | 9   |
| Ore              | 7    | 6   | 13 | 4       | 9   | 10  | 9   | 13  |      | 9   | 8  | 17                                        | 4  | 9   |
| Groundmass       | 27   | 26  | 26 | 13      | 21  | 16  | 13  | 14  | 59   | 15  | 19 | 1                                         | 42 | 23  |
| Other            |      |     |    | biotite |     |     | 0.6 |     |      |     |    | rutile 0.5<br>nepheline<br>apatite 6<br>2 |    |     |
| Texture          | B    | B   | B  | Peg     | BC  | A-B | B   | A-B | C    | A-B | A  | A                                         | B  | B   |
| "Total Feldspar" | 34   | 33  | 32 | 31      | 31  | 28  | 22  | 20  |      | 32  | 29 | 46                                        |    | 32  |

TABLE 2—Localities of Rocks Analysed as Table 1

| Modal Analysis No. | Section No. | Centre            | Remarks                                                                                                                                                |
|--------------------|-------------|-------------------|--------------------------------------------------------------------------------------------------------------------------------------------------------|
| 1.                 | 4392        | One Tree Hill     | Ellerslie Racecourse at 25 ft depth in flow. Similar to 4407 same site (analysed Searle, 1959).                                                        |
| 2.                 | 4448        | One Tree Hill     | Selwyn St., Onehunga. Phenocrysts: Olivine 1.5 mm; augite 1.0 mm; labradorite 0.6 mm; ore aggregates 0.3 mm.                                           |
| 3.                 | 4955        | Rangitoto         | Islington Bay. Vesicular; corroded olivine 1.5 mm; augite 1.0 mm; labradorite 0.6 mm. Dendritic ore scattered through groundmass.                      |
| 4.                 | 4393        | Mt Albert         | Oakley Creek, Stewart Ave. Rare apatite needles in groundmass.                                                                                         |
| 5.                 | 4901        | Pukeiti           | Bridge, Ourangi Creek. Olivine 3 mm; augite (titaniferous) 0.8 mm; labradorite 0.4 mm.                                                                 |
| 6.                 | 5115        | Little Rangitoto  | Benson Road. Olivine 2.6 mm; augite 0.8 mm; labradorite 0.2 mm.                                                                                        |
| 7.                 | 1496        | Eden              | Craig's Quarry (eastern side, foot of cone). Augite little colour.                                                                                     |
| 8.                 | 5038        | Papatoetoe Crater | Flow in tuff ring. Pilotaxitic, augite dark and granular.                                                                                              |
| 9.                 | 5051        | Papatoetoe Crater | Flow in tuff crater. Analysed. Augite pale mauve. Ore in large aggregates. Olivine anhedral.                                                           |
| 10.                | 4384        | Wellington        | Near Glassworks, Penrose. Augite-brownish. 0.8 mm; olivine anhedral, 1.2 mm; feldspar laths 0.3 mm. Apatite and late pyroxene needles in residual fsp. |
| 11.                | 4373        | Albert            | Owairaka Boys' Home. Olivine 2.5 mm. Feldspar laths 0.5 mm; augite 0.8 mm, dark, zoned.                                                                |
| 12.                | 4911        | Eden              | Almorah Road, Newmarket. Olivine (with iddingsite) 2.5 mm; augite; pale mauve, and golden yellow, 1.0 mm; feldspar laths 0.2 mm.                       |
| 13.                | 4390        | Wiri              | Olivine, 3 mm; augite deep mauve and zoned, 1 mm.                                                                                                      |
| 14.                | 1970        | Duders Hill       | Flow on shore. Analysed. Olivine often euhedral, 0.8 mm; augite 0.6 mm; fsp. almost limited to residuum; abundant magnetite.                           |
| 15.                | 4372        | Three Kings       | Flow inside tuff ring. Olivine anhedral and embayed; pyroxene mauve; much brown glass; labradorite laths.                                              |
| 16.                | 4376        | Roskill           | Martin Ave. Olivine enwrapping picotitic spinel and often rimmed with pyroxene; pyroxene mauve-brown; needles of apatite and ore in residuum.          |

TABLE 2—Localities of Rocks Analysed as Table 1—*continued*

| Modal Analysis No. | Section No. | Centre         | Remarks                                                                                                                                                             |
|--------------------|-------------|----------------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| 17.                | 5122        | Albert Park    | Cnr. Queen and Victoria Streets. Olivine anhedral, embayed; augite mauve.                                                                                           |
| 18.                | 4397        | One Tree Hill  | Korma Mills. Olivine 1 mm, rounded and rimmed with pyroxene; augite purplish 0.6 mm; ore coarse, 0.2 mm.                                                            |
| 19.                | 4385        | Wellington     | Michaels Road. Olivine 1 mm. anhedral; augite 0.2 mm., granular; fsp. 0.3 mm., basic labradorite.                                                                   |
| 20.                | 5107        | Eden           | Olivine 1 mm., some euhedral, others anhedral with spinels. Augite dark purplish 0.5 mm., fsp. laths 0.8 mm; ore coarse.                                            |
| 21.                | 4921        | One Tree Hill  | Cnr. Kalmar St., and Gt. South Road. (National Brush Co.). Olivine 1.5 mm rounded and pyroxene-armoured; augite 1 mm. Biotite in scattered flakes, small to 0.4 mm. |
| 22.                | 4922        | Pigeon Mt.     | Olivine 2.5 mm rimmed with pyroxene; augite mauve, zoned, 1 mm.                                                                                                     |
| 23.                | 4377        | Richmond       | Flow basalt; glassy. Brown glass with corroded olivine and augite phenocrysts.                                                                                      |
| 24.                | 4658        | McLennans Hill | Flow basalt.                                                                                                                                                        |
| 25.                | 5053        | Hobson         | Olivines large, embayed, some rimmed with iddingsite. Augite granular, dark; plagioclase relatively large, 0.5 mm.                                                  |
| 26.                | 4380        | Eden           | Spatter area, Auckland Grammar School, Olivines rimmed and replaced by ore (?magnetite).                                                                            |
| 27.                | 4942        | Domain         | Coarse phase, nepheline dolerite.                                                                                                                                   |
| 28.                | 5137        | Green Hill     | Flow, Pakuranga Inlet. Olivine anhedral 2 mm; augite 0.8 mm, zoned purplish-brown. Lab-Bytownite phenocrysts 0.4 mm.                                                |

The data of Table 1 show that the bulk of local rocks are olivine basalts and augite-rich picrite basalts with the former slightly more numerous with respect to the particular sections analysed. These have been chosen to provide as wide a variety of types as possible and do not attempt to represent the distribution of these rocks in the field. Only a small proportion of the very large number of sections examined has been analysed with the point counter but care has been taken to sample flows from a large number of centres so that they afford a fairly comprehensive and not unrealistic coverage of the field.

The percentages of olivine in the flow rocks vary between 9 and 22%, and in the majority of sections studied the proportion is closer to the

latter figure. Augite, frequently with moderately strong body colour, particularly in outer zones, and with distinct pleochroism, constitutes as much as 40% of some rocks and in near holocrystalline varieties, usually makes up at least 30% of the volume. There is no sharp distinction in the size of individual crystals of pyroxene in the phenocrysts and in the groundmass of the rocks. They appear, rather, to form a continuous series indicative of the progressive separation of the mineral during continuance of the crystallisation of the basalt. Ore is always abundant and contributes approximately 10% to the volume of the sample with values ranging from as low as 4%, in some coarse-textured rocks, to as high as 17% in others. Magnetite is the dominant ore mineral and probably often carries a small quantity of titanium. Ilmenite is also common and in some circumstances haematite is abundant.

The amount of crystalline feldspar in the rock is determined in part by the chemical constitution of the lava and in part by the physical conditions that obtained during its solidification. Thus sections of rocks that have cooled rapidly, as near the surface of a flow, have a notably greater proportion of groundmass and fewer feldspar phenocrysts than those that cooled more slowly. On the other hand, late-formed segregations of residual liquid which appear to have solidified relatively slowly adopt a pegmatoid texture with a relatively large proportion of crystalline feldspar in an enveloping but coarse-grained residuum. Truly vitrophyric rocks which have been chilled to form selvages on blocks, bombs and occasionally on flows usually have only rare phenocrysts of feldspar.

Apatite, observed as an accessory mineral in a majority of sections, is usually present as minute prisms in the groundmass. In some sections, as, for example, those of the Domain basanite and of the doleritic phases of the North Shore basalts, it is abundant both in stout prisms and in slender needles. A few tiny plates of biotite were noted in a number of sections but it was also found as a notable constituent in relatively large flakes in a small group of rocks where it contributes as much as 0.5% of the bulk. Similarly, whilst rutile was observed frequently as a very rare accessory it was found in abundance in the rocks of a particular volcanic environment.

Other minerals important only in specific varieties of the basalts include nepheline in blocks from Auckland Domain, and the amphibole cummingtonite observed in a few sections of rocks from the Three Kings. Zeolites are not unusual as thin coatings lining the walls vesicles but in most cases these were so thin that they could not be resolved optically and therefore, with two exceptions, their species could not be determined.

### *Order of Crystallisation*

The relative size of the olivine phenocrysts and their frequently embayed margins indicate clearly that this mineral was a member of the early crystal fractions. Whilst euhedra are not uncommon, anhedral, corroded crystals and crystals with reaction rims are more abundant and provide evidence that early separation and re-solution of the olivine as a result of its reaction with the liquid phase of changing composition has generally been the case. The fact that olivine is seldom observed in other than the phenocrystic grade indicates that separation of the mineral had, in the main, ceased

before final solidification of the rock. Some of the olivines are apparently relics of border facies crystallate which has subsequently become incorporated in the lava. This is most clearly demonstrable in the case of the lavas of the North Shore volcanoes – Pupuke, Mt Cambria and North Head – where such relics include partly resorbed olivines of this latter type, often enclosing spinelid minerals that are distributed throughout the host mineral in an orderly array.

In the border facies crystallate, referred to above and considered in greater detail later, pyroxene has crystallised together with olivine at an early stage in the solidification of the magma. Nevertheless it is clear that the bulk of the pyroxene in the lavas separated after the greater part of the olivine had separated. Insets of pyroxene are seldom found to have a size as great as that of the above; phenocrysts of olivine are frequently enwrapped by augite. In the basalts the augite is almost wholly in euhedral individuals of all grades in size and occurs also in glomerophenocrysts sometimes surrounding rounded kernels of olivine or as a thin armour about olivine phenocrysts. Furthermore, it is clear that once started the separation of pyroxene persisted as a continuous process until solidification was complete. Indeed, in some sections where residual liquid has been separated at a late stage it is found to contain microphenocrystic pyroxene. Again, in other rocks vesicles have a lining of a sulphur yellow variety of the mineral found both as a dense matte on the walls of the vesicles and as tiny needles projecting into the cavities.

The usual changes in composition of pyroxene which separates during the course of crystal growth in a liquid phase of altering constitution is evidenced by difference in colour and in optic properties of inner and outer zones of individuals. Whilst in many instances the changes indicated are of a very gradual nature, it is perhaps more common to find a sharp change during the later stages of crystal growth, resulting in the outer zones being more deeply coloured and more highly pleochroic than those formed earlier. If the depth of mauve colouring can be taken as indicative of the titanium content of the pyroxene, then it would seem that, as a general rule, the later crystallised pyroxene is richer in titanium than the earlier, and that the greater part of the titanium ions of the liquid phase do not separate or are not able to enter the pyroxene lattice until the later stages of solidification of the melt are well in hand. The fact that granular pyroxene of the groundmass is generally darker in colour than the larger insets would appear to support this contention. It is worthy of note, in this connection, that small segregations of pegmatoid character in the basalts of North Shore (Fig. 1), which may best be explained as late crystallate of residual material squeezed out of the mush of partly crystallised basalt, contain particularly deep coloured titanaugite together with abundant needles of apatite and skeletal aggregates of ilmenite – typical late stage minerals. In the majority of these Auckland basalts the bulk of feldspar has been moderately late in crystallising. This is suggested by the relatively small proportion of plagioclase in the phenocrystic grade, by the typically small size of the laths with respect to that of olivine and pyroxene and by the general lack of zoning shown by the phenocrysts. Furthermore, in glassy rocks (e.g., 4377) phenocrysts of feldspar are commonly absent or rare

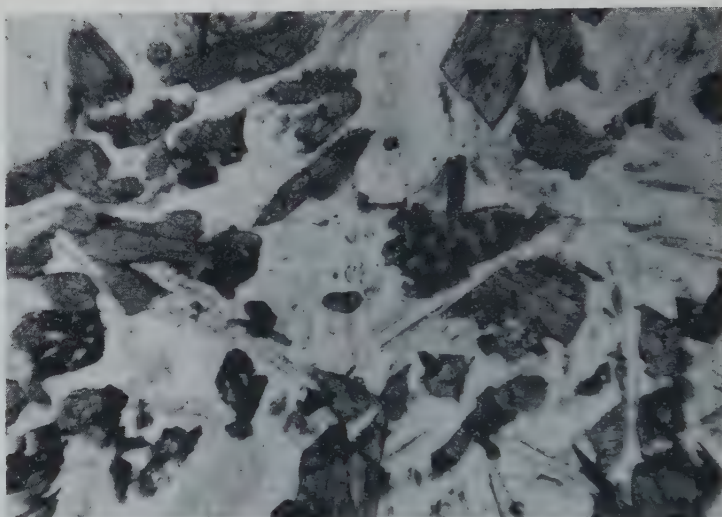


FIG. 1—Pegmatoid segregation in late crystallate of Pupuke lavas. Titanaugite and skeletal crystals of ilmenite with plagioclase laths in a coarse-grained crystallisation of feldspar. (1409)  $\times 38$ .

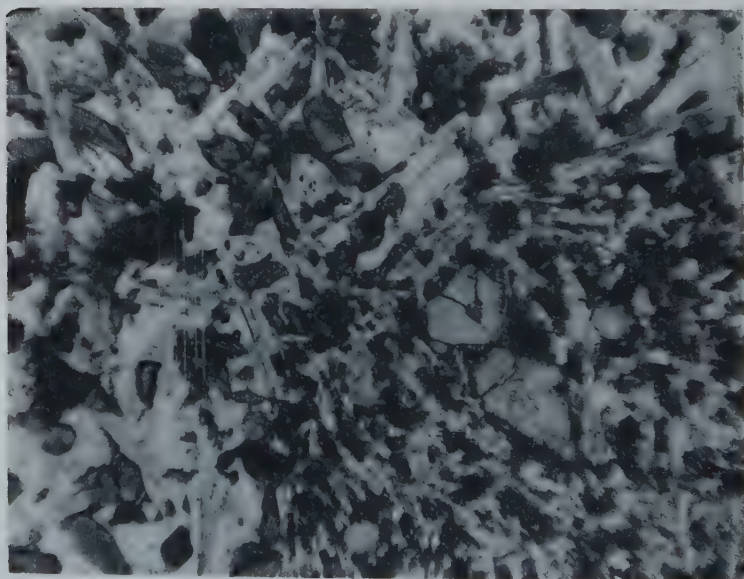


FIG. 2—Interface between pegmatoid segregation (left and top) and olivine basalt (lower right) in Pupuke basalt. (1409)  $\times 38$ .

whilst quite coarse feldspar is typical of late crystallised fractions. In the case of ultrabasic inclusions in the basalts and of fragments of similar nature in some of the tuff bodies, which have been interpreted as an early crystallate of border facies type, feldspar is seldom present.

Accessory minerals such as the bulk of the ores, rutile, biotite, and apatite have generally been late in forming and are seldom enwrapped by other than residual feldspar. Ilmenite, on occasion, appears to have crystallised very rapidly, just before the final solidification of the residual liquid, for it there occurs as very large aggregates in the form of slender rods building skeletal forms penetrating the groundmass. In the biotite-rich basalts the mica is in plates which are large and somewhat corroded; textural relationships show that they have obviously been formed elements in the lava well before solidification of the groundmass had got under way.

### GENERAL PETROGRAPHY

#### (1) *Olivine Basalt*

Rocks of this type are characteristic of the major flows of the main lava-producing centres, such as Mt Eden, One Tree Hill and Rangitoto, which contributed most freely to the building of wide lava fields surrounding these volcanoes. From the point of view of total bulk they may well be regarded as the dominant effusive rocks of the Auckland volcanic field.

Typical sections (e.g., 4392, Fig. 3), show the rock to be coarse-grained,

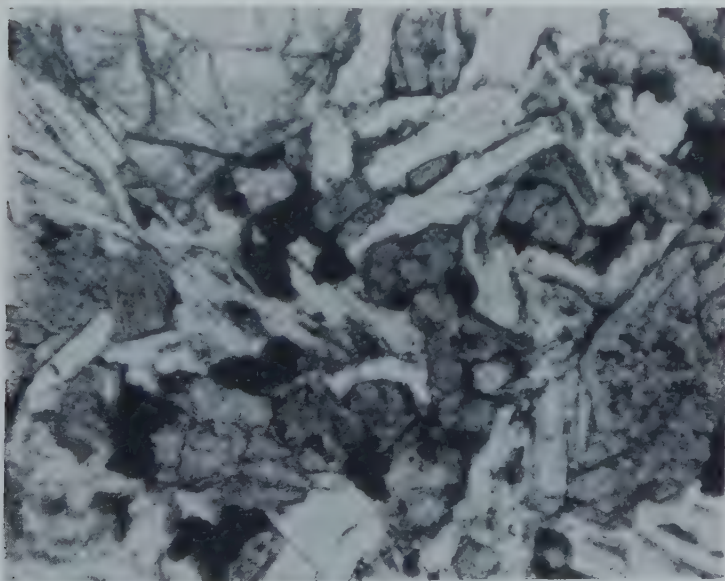


FIG. 3—Intergranular olivine basalt from lava of Wiri volcano. Euhedral olivine with granular augite and coarse aggregates of magnetite. On right olivine enwraps clots of ore. (4392)  $\times 100$ .

medium grey and dense, with textures ranging between intergranular and intersertal, often with blebs of brown glass present in the groundmass. Olivine phenocrysts as much as 3.0 mm in longest dimension are both euhedral and rounded with corroded margins. Pyroxene (diopsidic augite) is rather granular, lightly coloured a pale yellowish orange and only faintly pleochroic; few individuals have lengths greater than 0.3 mm. Feldspar laths, with maximum length of 0.6 mm are abundant (Fig. 4) and consti-

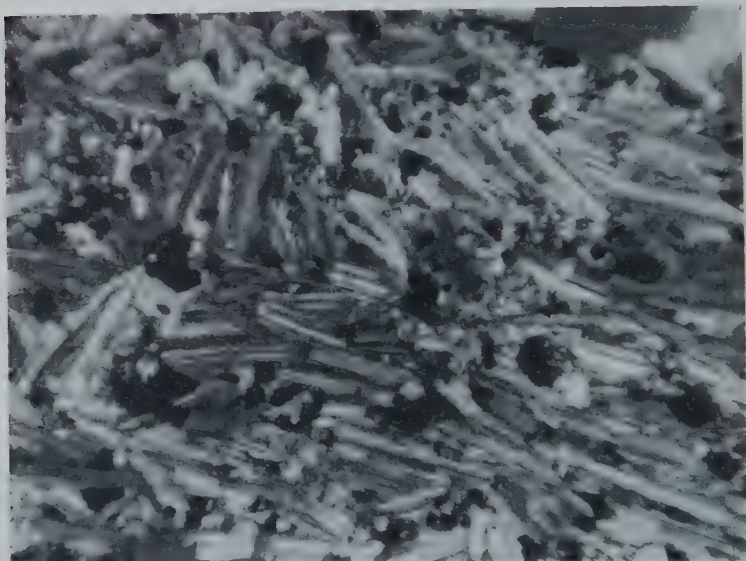


FIG. 4.—Feldspar-rich variety of olivine basalt. Microphenocrysts of basic labradorite with granular pyroxene and coarse euhedral magnetite. (4380)  $\times 125$ .

tute, in some sections, almost half the bulk of the rock, although in most olivine basalts it is much less abundant, and in the majority of sections examined the laths make up less than 25% of the volume. In these sections most of the feldspar present is represented by the groundmass. The laths are sometimes fluxionally arranged but more often they are randomly disposed. The phenocrysts are generally basic labradorite in composition; the groundmass is often a close-textured mass of interlocking rather indistinct individuals. Abundant ore, mostly magnetite in granules less than 0.1 mm in diameter, and rare apatite are scattered throughout the groundmass.

Rocks within the group vary considerably both in the relative proportions of the constituents and in texture. They are generally lightish in colour but differ little in this respect from the other basaltic rocks of the area. In section the most noticeable characteristic is the relative abundance of phenocrystic feldspar.

## (2) *Augite-rich Picrite Basalts*

These rocks are characteristic of the flows of many of the smaller volcanoes and of the lesser and usually older flows of the larger ones. They vary little from flow to flow or from centre to centre. They include those obviously basic types which Bartrum (1942) and Firth (1930) referred to as near limburgites in composition, but are far more common in the Auckland field than they were earlier assumed to be.

In hand specimen they resemble the olivine basalts but as a group are very slightly darker in colour and denser in appearance. In rocks of 'intersertal' texture, true glass is less common, being replaced in the fabric by an alkali-rich feldspar of cryptocrystalline habit.

Olivine phenocrysts occur in much the same proportions, size and form as they do in the olivine basalts. They are commonly approximately 1.0 mm in longest dimension and range up to as much as 3.0 mm, occurring in separate insets or less frequently in groups of two or three individuals. As in the olivine basalts the mineral is almost always unweathered but is occasionally rimmed lightly with iddingsite. Few grains of olivine are encountered in the groundmass or even in the microphenocrystic grade. However, there is evidence of minor separation of olivine at a late stage in the solidification of the lava, as has been observed by the writer (Searle, 1958), in the thin lithic septae formed in the shrinkage cracks of carbonised wood encompassed and invaded by lava, and in several sections where small olivines were observed in fine-grained later crystallate that occupied embayments and fractures in corroded phenocrysts.

Pyroxene is generally more abundant than olivine and is often wholly granular with small euhedral grains ranging in size to 0.8 mm (Fig. 5).



FIG. 5—Typical augite-rich picrite basalt. Intergranular fabric with euhedral and granular titanaugite, abundant magnetite and laths of basic labradorite. (4373)  $\times 100$ .

Glomerophenocrysts composed of many individuals in clusters or stellate aggregates were frequently seen. The augite is much darker in colour than in the olivine basalts, is typically titaniferous and more strongly zoned. Outer zones, in particular, are often strongly pleochroic, from mauve or brownish mauve to greyish or yellowish mauve in colour. Ore is abundant and dominantly is magnetite in scattered granules and euhedra, often in aggregates with diameter as great as 0.5 mm in length. Irregular clots of magnetite are commonly clustered about olivine and augite inlets.

Plagioclase is usually in laths twinned according to the Carlsbad and Albite laws and less frequently shows zonal structure; the laths are usually small and randomly oriented. In many sections feldspar is an inconspicuous constituent both because of the size and number of laths. In others the laths are few but may be relatively large (0.5 mm), whilst, again, other sections have feldspar limited to the small slender laths of a holocrystalline groundmass. The composition of phenocrystal feldspar is in the range labradorite – bytownite.

### (3) *Picrite Basalt with Biotite*

As already noted, biotite is a rare component of the groundmass of a number of the sections examined. In such cases it occurs in sharply bounded rectangular flakes or as minute red-brown pseudo-hexagonal plates. This is the case, for example, in sections such as those from doleritic phases of the Pupuke basalt. Re-fused rocks such as 4088 and 4381 have very minute plates and the mineral is occasionally found in a similar form in basalt close to the interface of fused sedimentary xenoliths.

In sections cut from the lavas of Pigeon Mt, and in some cases from the flow rocks of Mt Wellington and One Tree Hill volcanoes it is more abundant. The flakes are larger, more corroded and highly pleochroic ( $x$  = pale yellow;  $y$  = light brown;  $z$  = dark brown;  $r > v$  strong).

In section 4921, from the flows of Mt Wellington, the flakes attain the size of 0.4 mm – as large as most of the other components of the phenocrystic grade – and constitute approximately 0.5% of the rock by volume.

Other sections of picrite basalts with noteworthy biotite are 4922, 4923, 5056 and 5087.

### (4) *Nepheline Basanite*

The nepheline-bearing rocks, found only as juvenile blocks in the tuff and scoria mounds of the Auckland Domain were described and identified as nepheline basanites by Marshall (1907, 1912). Bartrum (1912) refers to them as nepheline dolerites and Benson (1942) has compared them with the other alkaline rocks of New Zealand and described them as nepheline basanite pegmatoid. Searle (1959) discussed their chemical nature and suggested that they represented a late-stage differentiate of the alkaline basaltic magma that is the common parent of all the volcanoes of the Auckland field.

Sections show that the rocks are characterised texturally by a pronounced doleritic to pegmatoid texture and mineralogically by the presence of nepheline. Considerable variation is shown by different blocks of this alkaline rock. Some blocks, as shown by thin section 1459, for example, have an almost granitic fabric with very abundant, highly pleochroic, titanaugite which often shows marked zoning and hour-glass twins. Feldspar is in broad laths and also provides a groundmass studded with stumpy prisms and long needles of apatite (Fig. 6). Large, badly corroded prisms

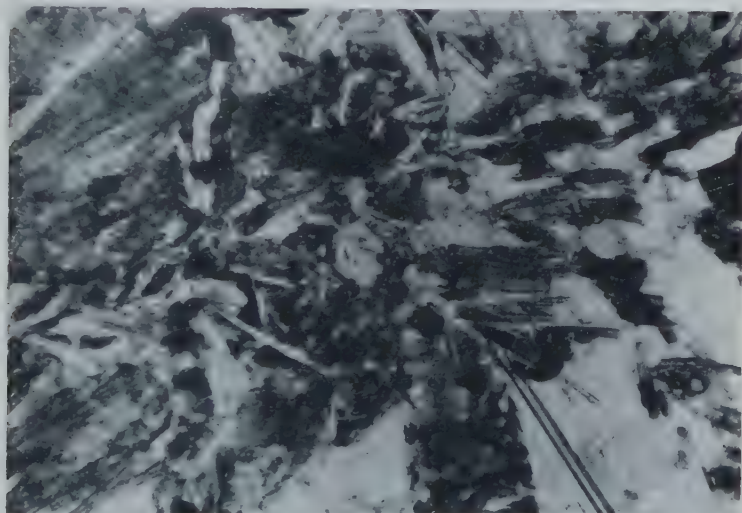


FIG. 6—Pegmatoid texture shown by Domain basanite. Sheafs of acicular augite and long needles of augite in a groundmass of rather plumose feldspar. (4695)  $\times 100$ .

of olivine are as much as 5.0 mm in length. Only minor nepheline is apparent in most of the sections but in section 4942 (Fig. 7) the feldspathoid is more abundant and constitutes 6% of the volume of the section. The texture of the rock is coarsely doleritic and the occurring nepheline is present in rectangular and hexagonal insets of as much as 0.4 mm in diameter. Textural relationships show that it was one of the last of the essential minerals to separate before the final solidification of the feldspathic residuum. Augite (Fig. 8) is dark mauve and strongly pleochroic, particularly in the outer zones. Palish green aegarine augite is occasionally a constituent (e.g., in 4944). It is found as rather slender prisms but more frequently it occurs in thin outer zones surrounding the mauve titanaugite. This suggests that sodium ions are unable to separate from the residuum and enter into the pyroxene lattice until concentrations are high and crystallisation is almost complete. In these, as in most sections, olivine is present in strings of optically continuous grains indicating that resorption of original large crystals had proceeded to an advanced stage before solidification of the rock became general. The olivine is more

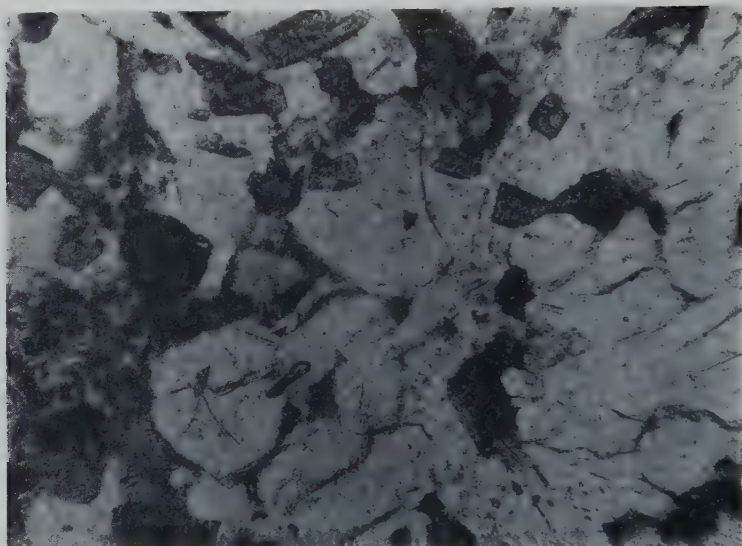


FIG. 7—Domain basanite showing euhedral insets of nepheline. (4942)  $\times 100$ .

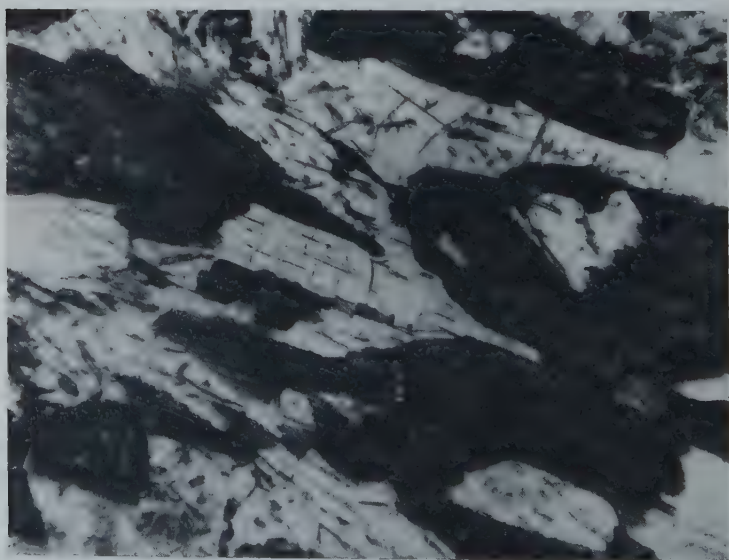


FIG. 8—Coarse phase of Domain basanite. Optically continuous titanaugite enclosed by a coarse crystallate of labradorite. (4695)  $\times 38$ .

fayalitic than is generally the case in the olivine basalts and picrite basalts of Auckland, for the majority of examples tested proved to be negative in sign and to have  $2V_x$  close to  $80^\circ$ .

In many of these sections the needles of apatite are finely developed being very slender with thicknesses approaching one-twentieth of the length and as much as 2 mm in length. Both magnetite and ilmenite occur in the groundmass, often in notably large aggregates; the ilmenite frequently builds up skeletal crystals approaching 0.5 mm in diameter (Fig. 9). The feldspar of the groundmass usually appears to be an alkali-rich variety being positive in sign and having a low refractive index.

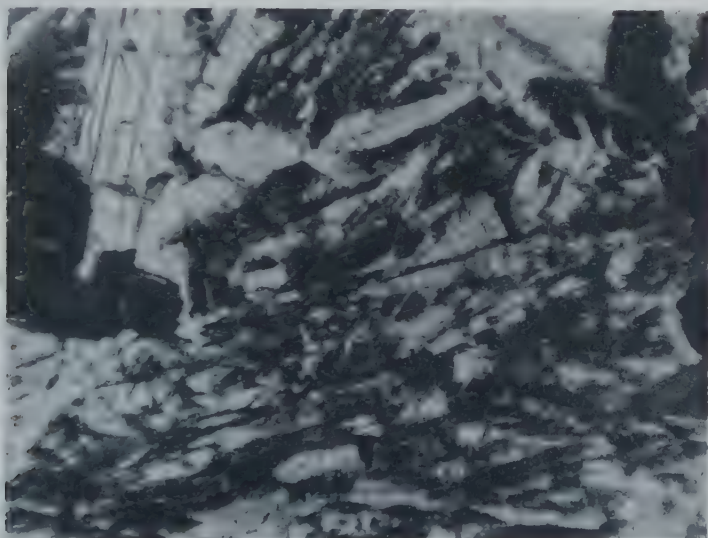


FIG. 9—Domain basanite acicular augite and large skeletal aggregates of ilmenite set in coarsely crystalline labradorite. (4695)  $\times 45$ .

#### (5) *Amphibole (cummingtonite) Basalt*

Brown amphibole is a characteristic component of a small number of sections of basalt associated with an irregular dyke intruded into the scoria of one of the cones of the Three Kings system of volcanoes. In section No. 5082 this amphibole occurs in phenocrysts as large as 1.0 mm in longest dimension and constitutes as much as 12% of the bulk of the section. The amphibole has the following optical properties:

$$\begin{aligned} &\text{Optically positive.} \\ &2V_z = 86^\circ \\ &Z_{\Delta c} = 12^\circ-14^\circ \\ &r < v \end{aligned}$$

Pleochroism strong ( $x$  = light brown;  $y$  = light brown;  $z$  = dark brown).

The amphibole is therefore identified as cummingtonite.

The sections are unusual in other ways. Like many of those described below, type 6, they were cut from the material of the irregular dyke referred to above, or from the material of fused scoriae adjacent to the dyke, which had presumably been remelted by gaseous emanations originating from it. The boundary of the dyke is not a sharply marked one but a transitional zone passing from dyke rock through remelted scoria surrounding "gas ways" that conducted emanations, and welded scoria fragments into loose clinkery scoria. In this respect the relationship between the dyke and the intruded scoria is analogous to that already described by Searle and Bartrum (1948) at Mt Wellington, where a group of hollow dykes cut through the scoria of that cone and are associated with pipes of welded scoria, glazed on the inside by hot gases from the intrusion. Comparable irregular intrusive bodies have been observed in other of the small cones of the Auckland field, e.g., that in Papatoetoe crater, although detailed petrological examination of the various rocks about the dykes has not yet been carried out.

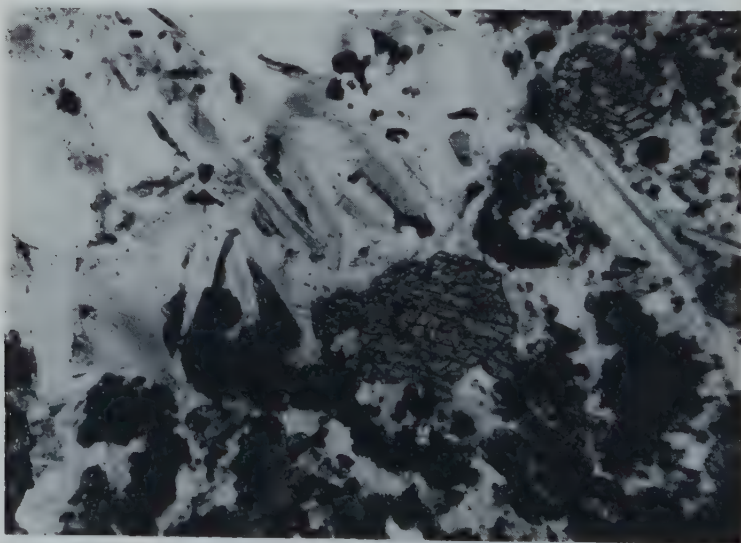


FIG. 10—Amphibole (cummingtonite) basanite, Three Kings Volcano. Parallel polars. (5082)  $\times 100$ .

Evidence of the agency of heat is afforded by several characteristics of these contact rocks. Olivine has largely been haematized to opaque red-reflecting pseudomorphs, pyroxene is in part a medium-brown almost certainly ferri-ferrous variety and in part a sulphur yellow variety. Accessory minerals include rutile in euhedral prisms scattered throughout the matrix, abundant magnetite, and ilmenite that is partly converted to leucocene.

A modal analysis (volumes per cent) of section 5082 is as follows:

|                        |                           |
|------------------------|---------------------------|
| olivine                | 2%                        |
| haematite              | 16 (olivine pseudomorphs) |
| other ore              | 13                        |
| pyroxene               | 23                        |
| cummingtonite          | 12                        |
| feldspar               | 19 (basic labradorite)    |
| feldspathic groundmass | 15                        |

The amphibole is restricted to patches of doleritic textured basalt; elsewhere the fabric is intersertal with granular pyroxene predominating. This latter mineral is normally pale in colour in the kernels but with outer zones of dark amber-brown. An area composed solely of stumpy prisms of sulphur-yellow pyroxene may represent a late-crystallisation of segregated material or possibly the pyroxene armour formed about a partly resorbed xenolithic inclusion such as was encountered in many other sections from a variety of sources.

#### (6) *Rutile-rich Picrite Basalt*

Rutile appears as an abundant constituent of the sections of a number of rocks (Fig. 11), particularly of those associated with spatter cone deposits, with dykes that have intruded scoria deposits, and with the irregular and highly vesicular basalt masses filling the throats of small vents. The rutile occurs both as needles and prisms in the body of the rock and also as

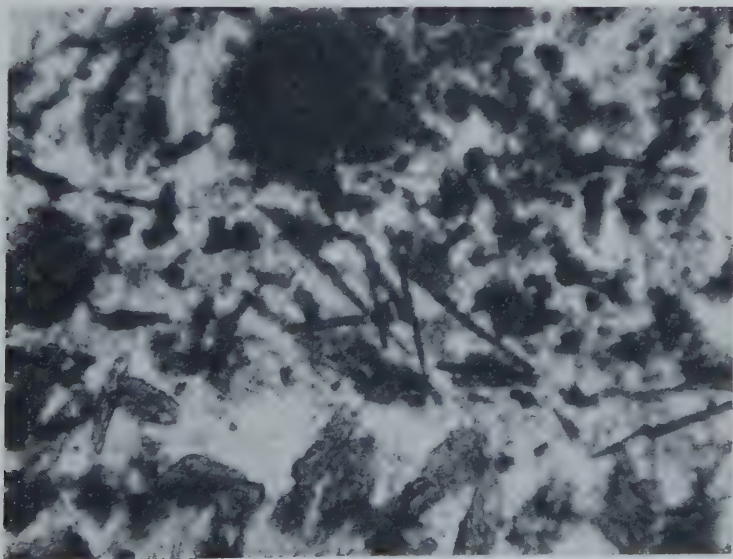


FIG. 11—Rutile basalt, Three Kings volcano. Rutile (dark needles), haematized olivine (top), augite and magnetite in a cryptocrystalline groundmass. The fine needles, in groundmass are sulphur-yellow pyroxene. (5080)  $\times 100$ .

needles lining the numerous vesicles. In these latter occurrences it is accompanied by prisms of sulphur-yellow pyroxene and the pseudocubic rhombohedra of haematite. The rutile would appear to be in part of deuteric and in part of primary origin.

The solid rock at a spatter cone on the surface of a Mt Eden lava flow in the grounds of the Auckland Grammar School appears to have been much affected by the roasting action of exhaled gases. The area, recently levelled and formed into a hockey ground, was formerly dominated by a small knoll of spatter materials piled up to a height of 30–40 ft above the surface of the flow. A small cave, close to the base of the knoll as noted by Bartrum and Searle (1948), was characterised by a roof glazed on the surface and studded with button stalactites indicating fluxion by released and reacting gases. The lava was grooved in places as a result of differential movement whilst the rock was in a plastic condition.

In the knoll itself small tongues of lava had been squeezed into the pyroclastic material from time to time, giving piles of small sheeted dykes and fluxing adjacent scoriae. The latter, e.g., section No. 4380, have olivine phenocrysts rounded and enclosed by well-defined haloes of magnetite and occasionally with the whole of the phenocryst replaced by magnetite. In other phenocrysts the olivine has been replaced by pseudomorphs of haematite surrounded by a rim of granular magnetite. The pyroxene found in the sections is rather granular and of two types: a pale titanaugite such as is found commonly in most of the rocks of the eastern flows of Mt Eden; and a golden brown variety found only in these particular rocks and described more fully below. Rutile is in small squat prisms in most cases but a few long needles of the mineral were observed in the sections. In all, rutile makes up approximately 0.5% of the bulk of the rock.

Comparable rocks, in which rutile abounds, from other local volcanoes also characteristically have golden-brown, amber, or sulphur-yellow pyroxenes, although the normal pyroxene of flows that originate from the same centres is usually pale-mauve titanaugite. If these rutile-bearing rocks are indeed, as field association and physical characteristics would suggest, heat-altered and refluxed scoriaceous basalts, it seems not unlikely that rutile has been formed of titania derived from original titanaugite and ilmenite.

In such material from Three Kings some of the rock is light-coloured glassy slag highly vesicular with vesicles lined with sulphur-yellow pyroxene, haematite and needles of rutile as much as 5.0 mm in length and of thickness approximately one fortieth of the length. In the body of the rock small euhedra of forsteritic olivine ( $2V_z = 84^\circ$ ) is associated with brownish-yellow pyroxene ( $2V_z = 54^\circ$ – $56^\circ$ ) probably diopsidic, set in a residuum of glass and cryptocrystalline feldspar.

Encrusting haematite is also characteristic of the frothy glassy rocks associated with fumarolic or spatter activity in the cinders of Smales quarry at Pupuke, Takapuna, where basaltic extrusion seems to have taken place under a mass of scoria, lapilli and tuff. Lava stalactites and stalagmites formed in vacuities in the fused masses above the basalt in this locality have been described by Bartrum (1947). The glazed surfaces of these structures are also coated with tiny euhedra of haematite. This is true also of the stalactites and lava-drip rocks described by Searle (1948) from

cavernous basalts in the lava of Mt Wellington, at Penrose. In neither of these cases, however, is rutile a conspicuous member of the mineral assemblage.

The basaltic dyke at Three Kings, mentioned above, is of interest in another respect. In structure it is sheeted with a body of normal basaltic rock overlying and in contact with a sheet of sugary texture which is strained to such an extent that it shatters on the blow of a hammer. Indeed, it is so friable that at times it may readily be crushed between the fingers. This latter sheet of rock is characterised by a mottling, due to closely spaced grey spots. Microscopic examination, e.g. S/606, fails to reveal any satisfactory explanation of the spots, although the groundmass does show small areas consisting solely of feldspar that could conceivably be responsible. In the section, rutile is abundant, pyroxene is sulphur-yellow and both haematite and rare apatite are accessories.

This rock would appear to be comparable with those known as "sunburnt" basalts in which the mottling has been attributed by Pukall (1940) to supersaturation of the magma with gases or water vapour. The spherical grey spots are explained as being formed by the loss of capillary rock moisture when the gases could not escape. Tension due to the accumulating gases is presumed, as the rock cools, to cause cracking of the rock, the cracking being localised in the area of the spots as a result of the formation of tension-free regions in porous spaces which become nuclei for the liberation of latent tensions in the rock.

In the present instance the effect would seem to be in some measure related to the emplacement of the more massive overlying basalt, probably following rapidly after the emplacement of the "sunburnt" rock. The presence of rutile and yellow pyroxene which are found locally only in localities where rocks, either basalt or sedimentary xenoliths in contact with basalt, have been subject to baking, certainly suggests that some such roasting in an atmosphere of gaseous emanations has been operative here. It is possible that such baking could also facilitate the release of latent tensions throughout the rock and thus cause the development both of the sunspot markings and of the pseudo-perlitic character of the rock.

### (7) *Ultrabasic Nodules and Inclusions*

The presence of nodular masses of olivine in the lavas of the Pupuke volcano and in bombs of the Onepoto tuff cones was recorded by Shrewsbury (1891), and an analysis of similar material from the lapilli beds of Lake Pupuke was presented by Turner and Bartrum (1929). Searle (1959) adduced evidence for regarding them as derived from border facies crystallate associated with the upper regions of a magma body that supplied these volcanoes.

Turner and Verhoogen (1960, 201), in reviewing the association of these peridotite nodules with alkaline olivine basalts, are inclined to favour the view that these xenoliths, "in spite of their tendency to be concentrated in individual flows of a volcanic complex, may well have been transported from a very deep source — perhaps the outer part of the earth's mantle itself." They point to the oriented character of the olivine fabrics and to

the presence of minerals such as enstatite and picotite, otherwise absent from the enclosing rocks, as evidence of a deep-seated source. They note, too, that "it is becoming increasingly clear that volcanic eruptions commonly tap magma that has risen rapidly from great depths."

It is true that the pattern of eruptivity in the Auckland field tends to support an hypothesis of repeated and rapid uprise of small bodies of magma as if expelled by dilation of fissures in the greywacke basement. Nevertheless it is difficult to accept the nodules in the volcanic rocks of the North Shore volcanoes as derived from deep crustal or mantle sources. The fact that they are commonest in the debris of basically phreatic volcanoes, are rarer in the flow rocks of associated vents, and almost unknown in the great bulk of volcanic rocks from the other volcanoes in the field, points to an isolated source. That they are most abundant in the tuffaceous deposits suggests a concentration in the upper portion of the parent magma body. This would permit their expulsion by purely explosive eruption. The writer cannot readily visualise any mechanism of injection prior to eruption which would cause the segregation in the top of the ascending magma, of material transported from depth. Two possible explanations that seem to fit the case more satisfactorily are:

- (a) That the xenoliths are fragments of a peridotite body encountered and invaded by the ascending magma at shallow depth. Such ultrabasic intrusions are known in the Silverdale area only a few miles to the north and might well be enclosed in Onerahi beds if these underlie the Waitemata formation locally. There is evidence that the hydraulic limestones did cover the greywacke basement but was largely removed by erosion before deposition of the Waitemata sediments. It is not unlikely that remnants of this early Tertiary area are still present in some localities.
- (b) That the nodules represent fragments of early crystallate that formed a carapace on the magma chamber. Of these two explanations the latter appears as the more satisfactory. Although the possibility that the former alternative is correct cannot be excluded, in this article such ultrabasic xenoliths are referred to as border facies material.

The nodules are most abundant in the lapilli and cinder beds where they range from scattered grains to fragments as much as 2 in. in diameter. In the tuff deposits they are so numerous that beach concentrations, derived from erosion of the Onepoto tuff cone, were sufficiently rich in olivine to impart a yellow colour to the sands. This led to the erroneous name of Sulphur beach for a feature now obscured by the road approaches and administrative buildings of Auckland harbour bridge. In the Onepoto area the nodules are more often enclosed by the basalt of bomb fragments than existing as separate masses. Small xenoliths of comparable material in various stages of digestion or of armouring against reaction abound in the lavas of the North Shore volcanoes, particularly in those of Mt Cambria and North Head, but even at these centres the ultrabasic material is more common in fragmentary blocks rather than in the basalt of flows. Similar inclusions are found only rarely in the rocks of other volcanoes of the Auckland field. In hand specimen the nodules are yellowish-green to light-green

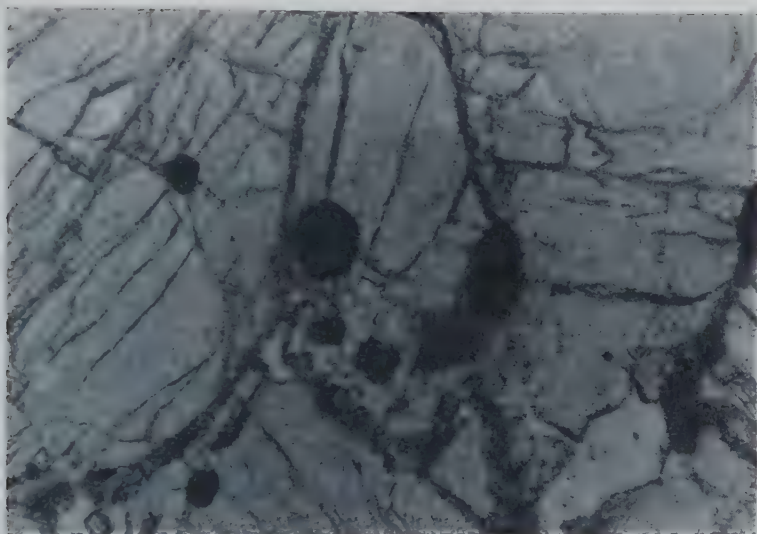


FIG. 12—Enstatite and olivine with clots of chromite in ultrabasic nodule from tuff of Onepoto Basin. (S/618)  $\times 70$ .

in colour and in texture rather sugary. Many are highly friable and shatter with pressure with the result that really good thin sections are difficult to prepare.

Thin sections (Fig. 12) show that the rocks range in composition between that of peridotites and that of hartzburgites. Some samples are composed almost exclusively of olivine while others have abundant (sometimes dominant) pyroxene together with the olivine. Both orthopyroxene and clinopyroxene are present; plagioclase is almost wholly lacking, and was, in fact, noted in only one of the many sections studied. Accessory minerals are almost limited to chromite, often in large irregular aggregates and a picotitic spinel in small euhedral octahedra. In section 1442 chromite makes up 8% of the section and some of the aggregates are as much as 2.0 mm in diameter. However the chromite is very unevenly distributed in the nodules and is abundant in only a small number of the sections; in many none was observed. The texture of these rocks is always granitic.

The ferromagnesian crystals are always anhedral and average about 1–2 mm in size, although optically continuous aggregates indicate that many single individuals may be very much larger. Olivine is always forsteritic with composition in the range  $Fa_{8-12}$  as determined from measurement of 2V according to the data of Poldervaart (1950). Many of the individuals show distinct cleavage parallel to (010) and others translation lamellae parallel to (100).

The commoner orthopyroxene is enstatite but hypersthene is also present in some sections and as relict crystals in sections of basalt. The clinopyroxene is diopsidic augite and in some instances has clearly developed by exsolution from host enstatite. In many sections evidence of reaction is preserved in a

frittering of margins of minerals and in the development of granular augite with occasional euhedra of olivine in thin veins between adjacent crystals. Small euhedral spinelids often occur in these veins of secondary crystallate.

Xenoliths of this border facies abound in the basalt of the North Shore volcanoes. They include fragments both of rock and of minerals obviously derived from it. Olivine often distinguishable from the truly phenocrystic olivine by the anhedral and corroded forms, and by the presence of translation lamellae, is often thinly overgrown with rims of iddingsite and with a thin armour of titanaugite. Xenoliths of both enstatite and hypersthene are usually bordered by striking, broad reaction rims, sometimes of titanaugite alone and sometimes of titanaugite with an intermediate zone of golden-yellow pyroxene. Many of the relics of clinopyroxene are partly resorbed – so that in extreme cases only a nondescript fibrous-looking mass survives – and then outgrown with palish-mauve augite comparable with that of the phenocrystic augite of the encompassing basalt (Fig. 13). The clinopyroxene of these “sweated” cores is in optical continuity with the later augite of the overgrowths which are usually built out from the irregularly shaped xenolithic pyroxene to give a euhedral form to the inset.

Fragments of rock and also of secondary crystallate are found surrounded by a similar armour of titanaugite – again often developed euhedrally. In no case was xenocrystic olivine found to be overgrown with olivine of later growth which suggests that at time of engulfment of the early crystallate the magma had largely passed the stage when olivine was separating freely.

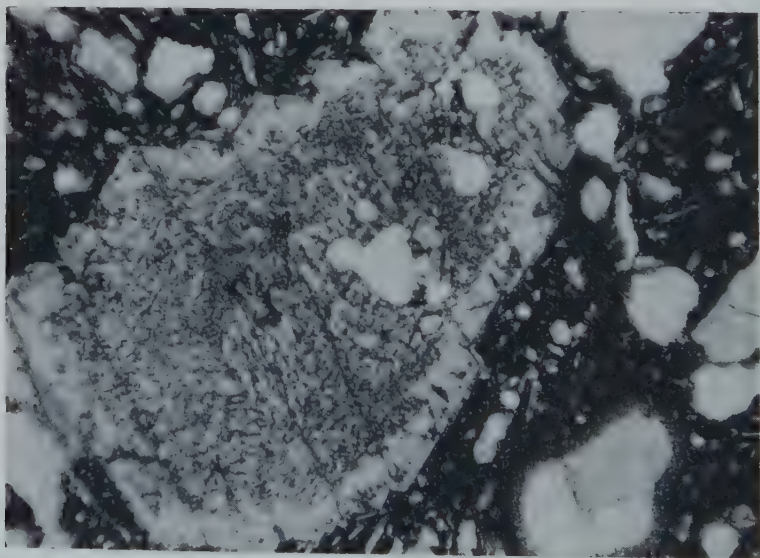


FIG. 13—Xenocryst of exsolved clinopyroxene from border facies crystallate overgrown with an euhedral mantle of zoned titanaugite. Cleavage traces are continuous through kernel and mantle. Lower right is an anhedral xenocryst of enstatite overgrown with sulphur-yellow granular pyroxene. (4913)  $\times 50$ .

## MINERALOGICAL NOTES

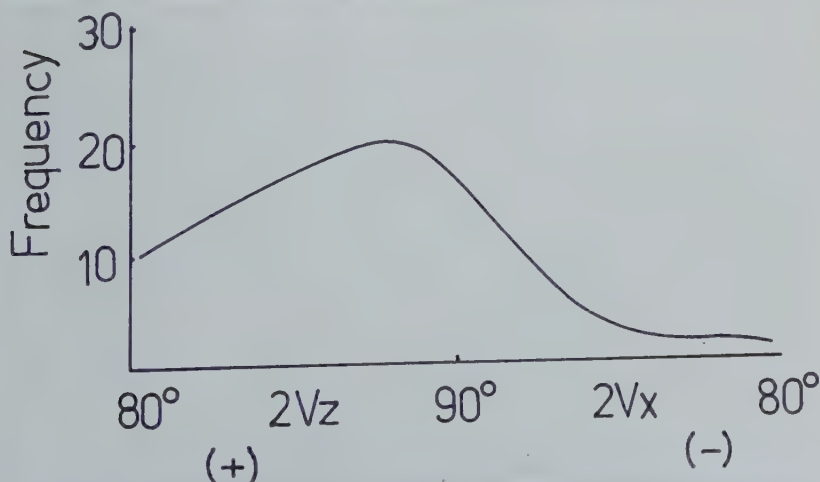
(1) *Olivine*

The Auckland basalts as a whole are particularly rich in phenocrystic olivine with insets more or less of one grade in size; as noted earlier, little of the olivine is in microphenocrystic grade or in granular elements of the groundmass. Whilst euhedral insets are by no means uncommon, much of the olivine is rounded and corroded and many insets are armoured with rims of pyroxene. These latter occurrences indicate that the olivine has separated early and in quantity in excess of stoichichemical proportions — a fact which is evident when the modes are compared with the norms. The euhedral forms suggest not only the reluctance of the system to resorb olivine but also possibly a tendency for the separation of olivine to continue in opposition to chemical balance in the liquid phase.

*Crystal forms:* Forms commonly present and identified by stereographic projection of face norms, determined by measurement on a universal stage were: (010), (100), (121), (021), (120), (101), and (110).

Cleavage or parting on (010) is usually weak and there is a distinct parting on (001) particularly well-marked in the olivines of the Wiri basalts. Euhedral insets are often tabular parallel to (100) resulting in elongated sections in which length is sometimes as much as 10 x breadth. Interpenetration twins, with (011) as twinning plane, similar to that described by Brothers (1959) in a flow basalt from Mt Eden, were encountered rarely. Scarcely a dozen examples were observed during the examination of some hundreds of sections each with 40–50 insets. Their frequency of occurrence must, therefore, be something of the order of one in a thousand phenocrysts.

*Optic Properties and Composition:* From a large number of determinations it is clear that the great majority of olivines of the olivine basalts and picrite basalts have an optical angle which is positive and close to  $90^\circ$ . Text Fig. 1 shows a frequency graph of 2V values. Clearly olivine in the



TEXT FIG. 1.—Distribution curve of values of 2V shown by phenocrystic olivine.

Auckland basalts is predominantly magnesian with composition in the range  $Fa_{10-15}$  according to the tables of Poldervaart (1950). Olivines more forsteritic in composition are commoner than are those more fayalitic than is covered by this range.

Determinations of refractive indices of olivines from a number of samples were all close and gave mean values as follows:

$$\left. \begin{array}{l} \alpha = 1.667 \\ \beta = 1.678 \\ \gamma = 1.697 \end{array} \right\} \pm 0.003. N_z - N_x = 0.030.$$

These figures, when applied to the data of Winchell (1951), indicate a composition conforming with that deduced from the optical angles of the maximum frequency group above. Zoned crystals are not common and outer zones are invariably thin when they are present. Such as were observed on optically positive cores had outer zones with values of  $2V$  smaller than those of the cores, whilst those that were negative had values of  $2V$  larger for outer zones than for cores. These facts indicate that in such cases the later crystallised olivine of the outer zones tended to be more magnesian than the earlier crystallised olivine of the cores. This is contrary to the findings of Hamilton (1956) and Johnston (1953) whose studies of zoned olivines led to the conclusion that as the separation of olivine from basaltic magma proceeds the olivine which crystallises tends to become progressively richer in iron. On the other hand Brothers (1960) in a recently completed study of olivine nodules from the Raglan district found that in zoned olivines from ultrabasic inclusions in basalts of that area, the opposite was the case and that outer zones were more forsteritic than were the inner ones.

It would seem that the sequence observed in the separation of olivine may vary in different bodies, for in the present study it was found that zoned olivines in the nepheline basanite of Auckland Domain differed from those of the typical flows of other local centres, in that outer zones were more iron rich than cores. In these rocks it is noteworthy that the olivine, as a whole is typically more fayalitic than that in the rocks of other local centres. The majority of crystals in the Domain rocks are negative in sign with  $2V_z$  ranging from  $76$  to  $86^\circ$ , indicating composition in the range  $Fa_{23-42}$  (Hyalosidinite) according to the data of Poldervaart (1950). Only a small number of crystals were optically positive, showing the presence of more forsteritic individuals. These observations are in conformity with those of Turner and Benson (1942), made on the olivines of four sections from the Auckland Domain. Refractive indices of olivine grains separated by a Franz isodynamic separator from a crushed sample of pegmatoid nepheline basalt were determined as follows:

$$\left. \begin{array}{l} \alpha = 1.702 \\ \beta = 1.728 \end{array} \right\} \pm 0.003 = Fa_{35} \text{ (in Poldervaart's curve).}$$

*Alteration:* In the Auckland volcanic field there is little, if any, evidence that hydrothermal activity has ever supervened as an important phase of eruption at any of the centres. Neither has normal chemical weathering

as yet had any deep effect on rocks other than pyroclastic materials so that flow basalts, even of the more eroded volcanoes (such as Albert Park), are still surprisingly fresh. Olivine, which is normally one of the first minerals to suffer change by chemical corrosion, is characteristically unweathered.

Changes most apparent in the olivine appear to have been caused by the heating and particularly by the roasting of rock in an oxidising environment. The rocks most affected are bomb material, scoriaceous basalt, superficial basalt of flows and notably scoriaceous basalt surrounding passageways through which have passed gaseous emanations from intruding dykes. In extreme cases, especially where there is evidence of roasting by hot gases, olivine has lost magnesia and silica, while iron has been oxidised to form red or brown pseudomorphs of haematite or goethite as described by Berry and Mason (1959). In less extreme cases the olivine has become darkened and made iridescent. Frenzel (1956) has noted that the reheating of volcanic rocks by later effusions causes various mineral alterations, especially those involving oxidation of ferrous to ferric oxides. There can be little doubt that similar changes can also be brought about by the heating of already solidified spatter material and scoriae by gases which may be sufficiently hot to remelt the dense basaltic rock of flows, as has been shown by Searle (1948) to have happened in at least one locality. Air drawn in by the hot blast through the porous and loosely packed material has no doubt played an important part both in attaining high temperatures necessary to cause melting and in providing an atmosphere favouring oxidation. Magnesium and silicon lost to the olivine has most probably been absorbed by the glassy mesostasis as there is no indication of late crystallisation of magnesian minerals in close proximity to the pseudomorphs. It is possible also that the yellow and brown pyroxenes found in some of the rocks of these types and apparently of diopsidic nature carry some magnesia expelled from the olivine; as already noted such pyroxene is sometimes found lining vesicles or encrusting the scoriaceous surface, and is therefore of late origin.

A second type of alteration, also apparently arising from the reheating of already solidified rock is similar to that described by Bartrum (1942) in a block of hyalopilitic basalt from Otahuhu. The olivine in this rock was characterised by the ubiquitous separation of iron ore in minute clots, often aggregated into rod-like or string-like bodies distributed through the olivine (Fig. 14). The periphery of the olivine insets was bordered by what Bartrum regarded as definite reaction zones of the same ore. Olivine similarly containing abundant finely granular iron ore dispersed throughout its crystals has been described by Macdonald (1949) from reddened blocks of picrite basalt ejected from Halemaumau and other Hawaiian centres. Bartrum regarded the iron ore as exsolved from an originally ferriferous olivine leading to the formation of the forsteritic variety of the mineral actually in the rock. He concluded, from the occurrence of similar olivine in a section of scoria from the summit cone of Rangitoto, that this alteration had taken place at a late stage in the volcanic history of the centre. Hence he deduced that the accepted view of progressive enrichment in iron and impoverishment in magnesium in olivines separating from a magma was not universal in its application.

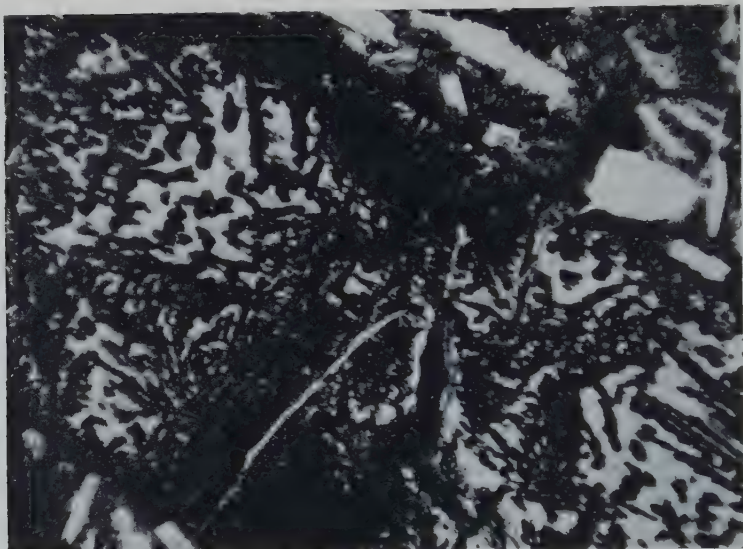


FIG. 14—Section No. 1531 showing rods and clots of iron ore distributed through a large phenocryst of olivine.  $\times 125$ .

However, this explanation may be regarded as doubtful for several reasons. Firstly, a fayalitic composition is not usual for the olivine in the local olivine basalts and picrite basalts. Secondly, the peripheral aggregates of ore are not clearly reaction rims in the sense that they have been formed by the interaction of an early crystallate with an encompassing liquid phase. And lastly, the rocks in which the phenomena are described are in all cases from very restricted physical environments. The present survey indicates that such olivine is not as unusual as Bartrum supposed it to be but, rather, that it is commonly encountered in rocks of these particular locations. It is not unlikely, indeed that such olivines could be regarded as characteristic of this type of rock and that they were considered to be unusual by Bartrum simply because the local sections with which he was familiar were almost entirely limited to those cut from flow rocks; his collection of thin sections contains few others. In the larger number, and more diverse types of basaltic rocks examined in the course of the present study many examples of these ore-invaded olivines were observed. In all cases the field associations of the rocks involved were such as to support the contention that they had been subject to the effects of heating after they had solidified.

In many sections of scoriaceous basalts and of basalts that have clearly been reheated, the ore dispersed through the olivine is magnetite. In some examples, e.g., in sections 4967, 4450, 5055, the ore forms an opaque border about olivine insets. Others show individual olivines at all stages of replacement by ore, from those in which ore is in delicate rods and plates, often oriented perpendicular to the faces of the host crystal, to those in which the olivine has been completely replaced by granular magnetite, e.g., 4380,

from the spatter cone on Mt Eden lava at Auckland Grammar School. Other sections from rocks of the same locality have a border zone on the pseudomorph after olivine which is magnetite surrounding a broad central area where the olivine has been replaced by a red-reflecting ore. Such an association appears to represent an intermediate stage in the formation of the complete replacement by magnetite but this would seem unlikely on chemical grounds. If the latter view is correct it would then seem necessary to postulate that the magnetite rim was formed after the haematite pseudomorph had formed.

In both these types of alteration and replacement of olivine difficulty arises from the relatively small amount of iron presumably carried by the olivine and the extent of ore making the replacement. Calculation shows that 1 ml of olivine of composition  $\text{Fa}_{20}$  would contain sufficient iron to provide only 0.14 ml of haematite or 0.24 ml of goethite. It is necessary therefore to suppose that, in progress of such alterations as those described above, either the outward movement of magnesium and silicon ions from the olivine is accompanied by an exchange involving acceptance of iron from the liquid phase, or that the magnesium and silicon form a medium of amorphous silica and magnesia in which the iron oxides are dispersed. It is not unrealistic to imagine that both processes may operate in the formation of the black and the red pseudomorphs.

Muir, Tilley and Scoon (1957) attribute the magnetite coronas surrounding olivine in picrite basalts of Kilauea to exsolution of iron, according to the equation



They conclude that iron must be introduced from the environment and that magnesium and silica move out in order that olivine of composition  $\text{Fa}_{20}$  should produce magnetite and hypersthene ( $\text{Fs}_{18-24}$ ). In the Hawaiian rocks the magnetite corona is surrounded by a wreath of hypersthene, and smaller olivines are replaced by intergrowth of magnetite and hypersthene. In the case of the Auckland rocks no orthopyroxene could be detected either in association with the magnetite or elsewhere in the sections. In examples where replacement was incomplete no significant change could be observed in the composition of small remnants of olivine as compared with larger almost unaltered olivines in the same section, or, for that matter, with respect to the olivines typical of the flow rocks in general. It may be that some such process as that suggested initiates the formation of a magnetite rim but it seems impossible to escape the conclusion that for broad rims the bulk of the iron has been derived from outside the olivine itself.

Dana (1921, p. 511) records that on heating in a bunsen burner varieties of olivine rich in iron fuse to a black magnetic globule. It would seem that a similar change may result when olivine is heated within the rock even when the olivine is more magnesian in composition.

The presence of iddingsite rims cannot be described as a common feature of Auckland basalts, and when they are seen surrounding olivine they are seldom thick, e.g., 1411, 1912, 1417. Iddingsite was never found to be completely replacing olivine. In a few examples, e.g., 4913, iddingsite coronas were themselves encompassed by a later growth of olivine, and in

one instance were overgrown by a pyroxene armour. These occurrences would appear to support the contention of Edwards (1938) that iddingsite is a deuteric mineral crystallised before the consolidation of the rock was complete. Ming-Shan Sun (1957) also concluded that iddingsite was deuteric in origin. He regarded it as an alteration product consisting of goethite in an amorphous complex of magnesia and silica. His elucidation of iddingsite as composed of cryptocrystalline goethite together with amorphous magnesia and silica makes it analogous to the constitution proposed for the opaque iron oxide pseudomorphs considered above. His experiments suggested that olivine was unattacked in various solutions and at different temperatures with a pressure of one atmosphere. In these experiments however, he does not appear to have employed temperatures as high as those that might reasonably be expected in a basaltic magma or in a situation where gas fluxing has occurred.

*Pyroxene Coronas:* In a great many sections occasional olivine phenocrysts were observed to be sheathed in reaction rims of clinopyroxene. Whilst the majority of phenocrysts do not carry such pyroxene coronas there is reason to believe that a not inconsiderable proportion of them are protected against reaction with the liquid phase by thin envelopes of this kind. Where the corona is more pronounced, it may be composed of granular pyroxene, e.g., 5066, 1418 (Figs 15 and 16), or of a cluster of pyroxene prisms growing out from the margin of the olivine, e.g., 5055, 4378 (Figs 17 and 18). A few individuals (1542, 4372) had rims of clinopyroxene developed over an inner sheath of granular ore surrounding the olivine.

Such coronas are, of course, not unusual. Kuno (1936) has described rims of hypersthene on olivine phenocrysts in basalt, and other authors

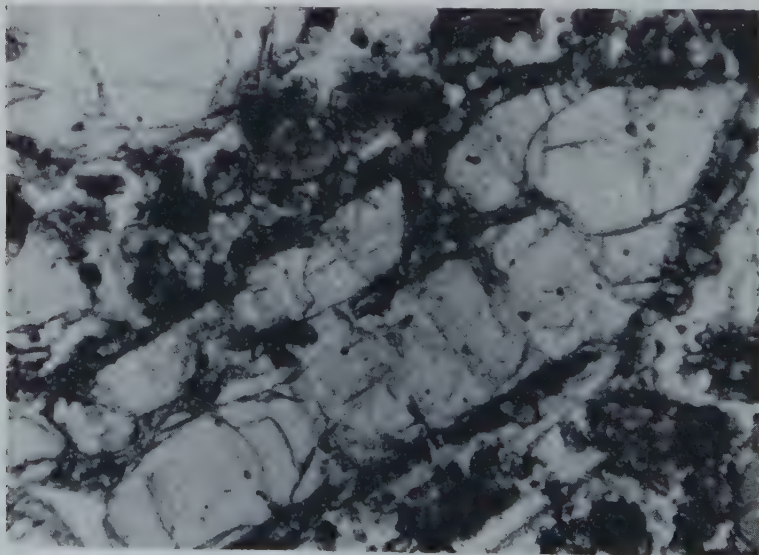


FIG. 15—Euhedral tabular phenocryst of olivine with corona of granular pyroxene. The olivine shows translation lamellae. Parallel polars. (5066)  $\times 100$ .

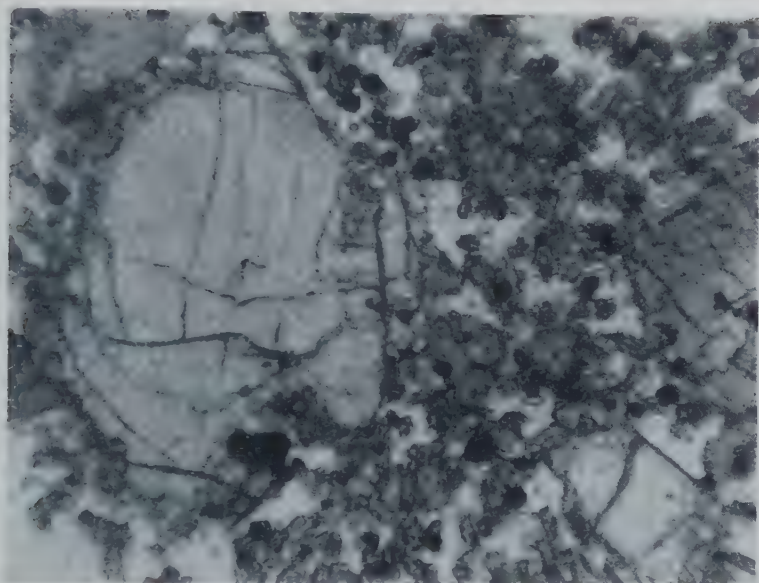


FIG. 16—Olivine, with light armour of pyroxene, in olivine-rich augite of One Tree Hill volcano. (4921)  $\times 100$ .

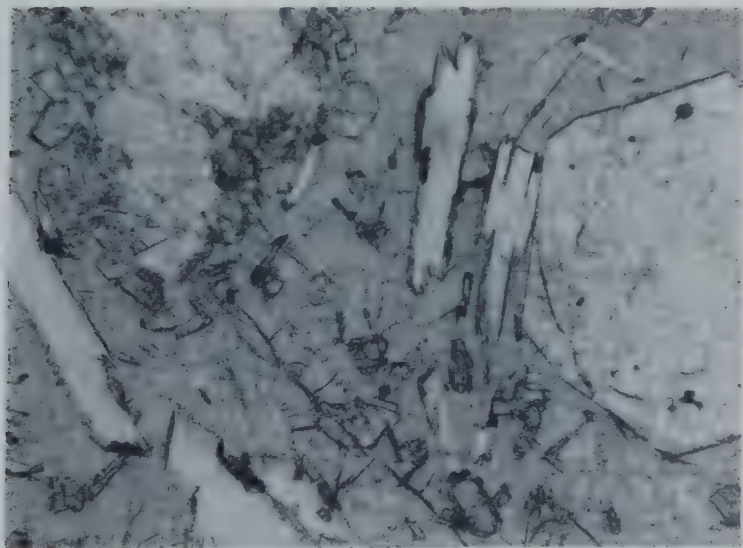


FIG. 17—Vitrophyric basalt with large phenocrysts of olivine — one anhedronal with olivine corona — small euhedral augites and laths of labradorite. (4378)  $\times 125$ .

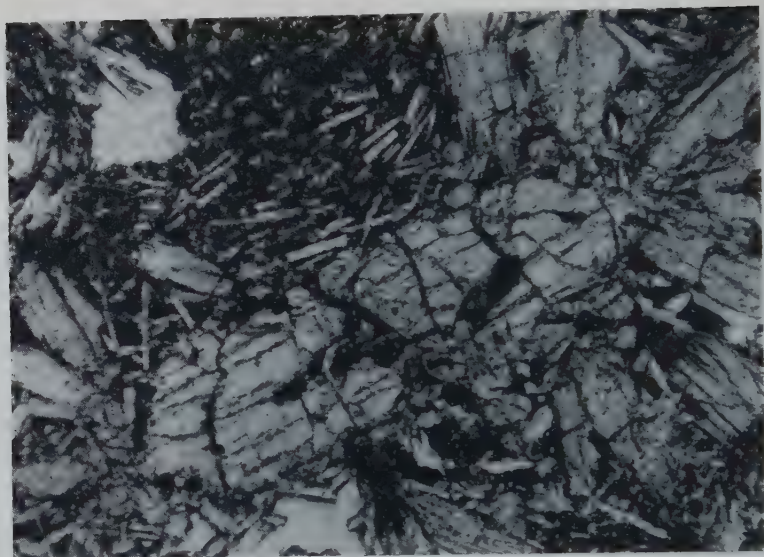


FIG. 18—Anhedral olivine with corona of radiating augite crystals from basalt of Mt St John. (5055)  $\times 100$ .

(e.g., Ellis, 1946; Shand, 1945) described olivine-hypersthene-cummingtonite reactions to explain the formation of coronas on the olivine of plutonites. In the present survey no orthopyroxene or amphibole was observed to have reaction relationship with olivine insets.

The development of reaction rims of clinopyroxene on olivine kernels may be accepted as resulting from the reaction: olivine + residual liquid  $\rightarrow$  clinopyroxene, arising directly from the discontinuous reaction series proposed by Bowen (1928). The reaction is regarded (e.g., Turner and Verhoogen, 1951, p. 86) as having failed to run to completion either because of rapid cooling or because of insufficient liquid in contact with the olivine crystals.

In this field it is evident from the large number of sections examined, that the great majority of olivine phenocrysts, apart from re-solution, are unaltered along their borders and that well-developed clinopyroxene coronas are relatively rare although thin films may be present more frequently. Only in the rocks of the North Shore volcanoes, which have patently been affected by the engulfment and partial assimilation of early crystallate, are such structures at all common. In the normal olivine basalts and picrite basalts of the area probably no more than one per cent of the olivine phenocrysts possess distinguishable mantles of clinopyroxene, and in these rocks, olivine phenocrysts are either euhedral or anhedral with margins embayed, as if by direct resorption by the liquid phase. Such embayments are usually invaded by mesostasis or by later crystallate. Examples of olivine coronas which were noted in these rocks were generally developed on euhedral or subhedral kernels and seldom on individuals that had suffered extensive resorption. This suggests that the formation of enwrapping

pyroxene has been successful in protecting the enclosed kernels from further reaction with the liquid. It would seem that the reaction: olivine + liquid  $\rightarrow$  clinopyroxene, generally results in ionic products absorbed directly into the liquid and that only rarely is clinopyroxene, as such, formed as a crystal phase about the olivine. When this does occur at the olivine-liquid interface, further reaction is prevented and the corona would then seem to grow by normal crystal growth by addition from the liquid rather than by continued development of clinopyroxene at the expense of the olivine within.

Sections cut from blocks from the tuff rings and from the lava flows of the North Shore volcanoes provide material of particular interest. In these rocks fragments of early crystallate — probably border facies material — have become incorporated in the lava. Individual xenolithic fragments show a variety of stages of digestion and reaction with the residual liquid of the lava. Some of the individuals provide very good evidence of two-stage development of coronas. Chemical reaction between the xenocryst and the liquid phase has resulted in the formation of a wide zone of granular pyroxene. This has been overgrown by the continuing crystallisation of coarsely crystalline pyroxene yielding a single or a few large pyroxene individuals enclosing the granular pyroxene and its corroded kernel. Some of the inclusions are gabbroid fragments, others are monomineralic fragments of olivine, orthopyroxene or clinopyroxene; all are abundant and occasionally more numerous than the truly phenocrystic individuals in the rock.

Rock fragments, derived clinopyroxene and, to a less extent, olivine are usually somewhat digested, but relict orthopyroxene, especially hypersthene, appeared to have suffered little by resorption after their incorporation in the lava. A few specific examples are cited as illustrative of what is commonly found. In section No. 4913, a large fragment of clinopyroxene (diopsidic augite) surrounds a kernel of hypersthene ( $2V_x = 84^\circ$ , suggesting a composition of  $En_{85}Of_{15}$ ) which is in optical alignment with other smaller relics of orthopyroxene scattered through the augite (Fig. 19). The hypersthene and augite are so oriented that  $X_{Hyp}$  and  $Y_{aug}$  have a common direction. The augite appears to have exsolved along 010 planes in the hypersthene. This change doubtless represents a reaction which had taken place in the early crystallate before its incorporation in the lava for similar replacements are observed in ultrabasic nodules found in the tuff bodies. The above unit is enwrapped with granular pyroxene in which individuals are too small for optical determination, and the whole is enclosed within a mantle titanaugite grown as a euhedral entity. This outside material is identical in optical properties with the phenocrystic pyroxene of the lava although a zone of granular pyroxene intervenes between the two, the titanaugite has grown in optical continuity with the diopsidic augite of the core. It would seem that after engulfment in the lava discontinuous reaction resulted in rapid formation of granular pyroxene deposited in grains oriented in alignment with the kernel. The granular material would then seem to have protected the kernel from further attack and at the same time to have provided nuclei for subsequent crystallisation of titanaugite in optical congruence with the core.

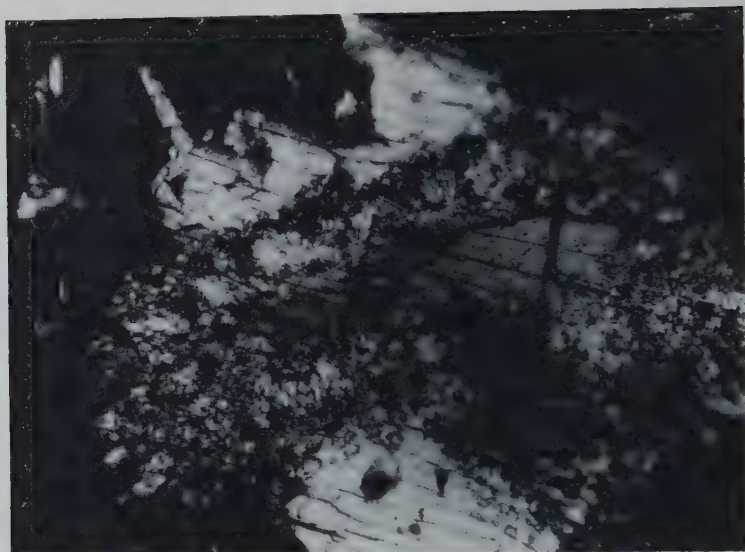


FIG. 19—Xenocryst of enstatite (darkish, central) with halo of granular yellow pyroxene overgrown with pale mauve titanite. Cleavage directions are common to both the clino- and ortho-pyroxene. Polars crossed. (4913)  $\times 100$ .

In section No. 4916 (Fig. 20) an anhedral grain of enstatite ( $2V_z = 78^\circ$ ), 0.5 mm diameter and with good (110) cleavage, has a broad reaction rim 0.04 mm thick made up of golden-yellow, granular pyroxene overgrown by mauve pleochroic augite in the form of a euhedral individual twinned on (100). The outer pyroxene mantle 0.1 mm thick is disposed relative to the enstatite of the kernel in such a way that  $X_{\text{enstatite}}$  (= a crystallographic axis) has a common direction with  $Y_{\text{augite}}$  (= b crystallographic axis); cleavage in both is parallel. That is, they have the same relationship as is commonly shown by clinopyroxene exsolved from enstatite. There is no doubt, however, that the clinopyroxene has originated by normal crystallisation from the liquid phase and not by any process of exsolution.

Other individuals in the same section (4916) include anhedral olivine rimmed with iddingsite and, in one or two instances, overgrown with pyroxene outside the iddingsite. Corroded clinopyroxene relics are common; some have no reaction rims, others are outgrown with titanite with or without a golden granular zone intermediate between the two.

## (2) Pyroxenes

The pyroxenes that have crystallised in the local olivine basalts and augite-rich picrite basalts, apart from those derived from border facies material described in the preceding section, are wholly clinopyroxene. Benson and Turner (1939) list optical properties of the pyroxenes in eight thin sections from Auckland, and include the determination of ortho-

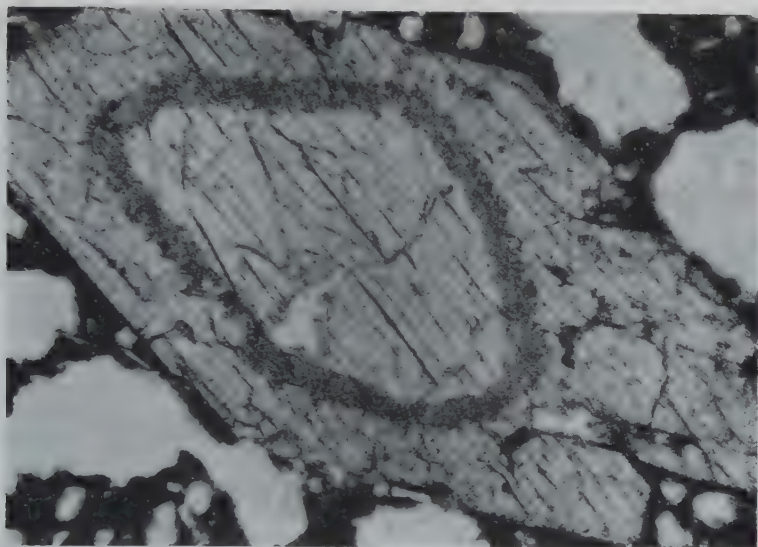


FIG. 20—Anhedral xenocryst of enstatite with corona of golden-yellow granular pyroxene overgrown euhedrally with titanite, twinned on 100. Cleavage direction is continuous on both kernel and overgrowth. (4916)  $\times 100$ .

pyroxene in the case of one individual in a sample from Rangitoto. However, this was later refuted by Benson and Turner (1940) and Turner (pers. comm. to Bartrum, dated 29.1/41). In the course of the present survey no orthopyroxene, other than that already noted, was observed in any of the many sections examined. Pigeonitic pyroxenes were also not encountered. The absence of these minerals from the assemblages in the local basalts is in accord with the conclusions of Wilkinson (1956) that such absence is characteristic of the alkali-plus-olivine magma type as opposed to the tholeiitic magma type.

Although clinopyroxenes were the only pyroxenes observed in the rocks they were not all of one type and variants of that commonly occurring were recorded in particular chemical and physical environments. The pyroxene group has so many variant components, whose effects on physical constants have not yet been adequately investigated, that determination of constitution on optic properties alone must be regarded as extremely hazardous. It is assumed that the possession of a mauve to purple body colour together with some degree of pleochroism is indicative of the presence of titanium, although artificial titaniferous pyroxenes are colourless (Segnit, 1953). Unfortunately, at present, no satisfactory data are available to permit valid correlation of composition of these titanium-bearing augites. Similarly orange brown, non-pleochroic varieties are assumed to owe their colour to ferric ions in the pyroxene lattice.

Varieties of pyroxene which have been encountered in the present survey are discussed below:

*Normal Pyroxene of the Auckland Basalts*

In the majority of sections examined clinopyroxene is the dominant mineral and occurs both among the phenocrysts and as granules in the groundmass. Insetts are seldom large and, apart from rare individuals, seldom have length greater than 0.6 mm. In both the olivine basalts and the picrite basalts pyroxene usually has some body colour and is at the most slightly pleochroic. In most cases the body colour is rather nondescript with a purple tint but in some of the picrite basalts it is faint to dark mauve and where the colour is stronger exhibits distinct pleochroism. Zonal structure is common in most large insetts and bears evidence to continuous reaction during the separation of the pyroxene. It is normally the case that the outer zones of phenocrysts are most deeply coloured than the inner ones, which suggests that titanium is disposed to enter the pyroxene lattice at a late stage in the process of solidification. It is noteworthy, too, that the pyroxene in the lavas of Pupuke (Takapuna) is pale coloured and poorly pleochroic whilst that in segregations of late stage crystallite is very deeply coloured and highly pleochroic. Whilst the outer zones of zonal crystals are often clearly demarked (and this is particularly the case where these are titaniferous) thus indicating some abrupt change in the composition of the pyroxene separating, the boundary between other zones is indistinct, and apparent only during examination between crossed nicols. In such crystals the optic properties change continuously rather than sharply. Almost universally such changes cause  $2V$  of outer zones to be smaller than  $2V$  of inner ones, and  $Z_{Ac}$  of outer zones to be greater than that of the inner.

The optic properties of the common clinopyroxene, either colourless or with slight body colour are constant for individuals in different flows and exhibit no greater variation than found between individual crystals in the rocks of particular flows. In no case were the optic properties of a clinopyroxene of this type found to be peculiar to any one flow or centre. Nor was any obvious distinction, based on optic properties, found to distinguish the augite of the groundmass from that of phenocrystic or microphenocrystic grades.

In a large number of crystals examined it was found that  $2V_z$  ranged from  $56-72^\circ$  with greatest frequency in the range  $66-68^\circ$  whilst  $Z_{Ac}$  (determined mostly on section approaching those perpendicular to two cleavages) ranged from  $41^\circ$  to  $52^\circ$  with greatest frequency in the range  $42-45^\circ$ . In all, it would seem that the dominant clinopyroxene is diopsidic but with some variation in composition. The determination tables of various authors do not permit composition to be defined more precisely as it may be inferred from the prevalence of pale pinkish colouration that titanium is generally present to some extent and the effect of this constituent on optic properties renders determinative data unreliable.

*Mauve and Purplish Pyroxene*

Whilst the bulk of pyroxenes in the Auckland basaltic rocks have some slight mauve body colour those of a few localities are strongly coloured and strongly pleochroic. Notable examples are found in the rocks of Auckland Domain, some phases of the Pupuke basalts, older flows of Mt Eden,

and the lavas of many other small centres. It is probable that most local pyroxenes carry a tenor of titanium and that some are comparatively rich in the element.

The ranges of optic properties of titanaugites from the Domain basanite were determined as follows:

Palish inner zones:

Range  $2V_z = 42-48^\circ$ ;  $z\Delta c = 47-52^\circ$ .

Dark outer zones or dark pleochroic individuals:

Range of  $2V_z = 63-64^\circ$ ;  $z\Delta c = 54-61^\circ$ .

Refractive indices of purplish pleochroic pyroxene were determined as:

$$\alpha = 1.680$$

$$\gamma = 1.707. \gamma - \alpha = 0.027$$

Hour glass twins were common. Dispersion was strong, occasionally causing anomalous extinction.

*Pleochroism*: X, pale-mauve; Y, dark-mauve; Z, reddish-purple. The refractive indices are close to those observed by Segnit (1953) for synthetic diopsidic augite with 4% titania but this author is careful to point out (p. 224) that his study of the optic properties of artificial pyroxene did not show significant changes that might be used for identification purposes. The low values of optic angle shown by kernels cannot be attributed to the content of titanium for it has been shown that the effect of this constituent in pyroxenes is to increase the optic angle.

The optic properties of dark pyroxene from Mt Eden, which may be regarded as more typical of the titanaugite in lavas over the whole field, were determined as follows:

$$2V_z = 59^\circ \text{ (inner zone)} \quad 47^\circ \text{ (outer zone)}$$

$$z\Delta c = 46^\circ$$

$$\alpha = 1.672; \beta = 1.680; \gamma = 1.697; \gamma - \alpha = 0.025.$$

Measurements were made, in all cases, on individuals twinned on 100.

### *Sulphur-Yellow Augite and Associated Minerals*

This pyroxene is characteristic of the heat-altered and refluxed basaltic rocks. It appears both in the body of the rock, as prisms in the ground-mass, in the glazed linings of vesicles, and occasionally as encrusting aggregates on the surface of scoriae. A similar pyroxene is also found close to fused or partly digested xenoliths of sedimentary material that form inclusion in the basalts of some localities. The optic properties of this pyroxene were determined from a number of individuals twinned on 100 and are as follows:

$$2V_z = 72-78^\circ$$

$$z\Delta c = 55-63^\circ$$

$$\alpha = 1.683$$

$$\beta = 1.705$$

$$\gamma = 1.753$$

$$\left. \begin{array}{l} \alpha = 1.683 \\ \beta = 1.705 \\ \gamma = 1.753 \end{array} \right\} \pm 0.003$$

Dispersion inclined; pleochroism faint. Twins on 100 as composition and twin plane are common; twinning often lamellar. Individuals occasionally contain minute plates of haematite.

A few rare and tiny crystals that appeared similar to, and were associated with pyroxene of the above type, were negative in sign, with  $2V_x = 84^\circ$ .

The optic properties suggest that the pyroxene may be a sodic variety of the diopside-acmite series with composition, according to the data of Winchell (1951, p. 414), of approximately 35% acmite. If this pyroxene is indeed sodic then the small optically negative individuals could be regarded as more sodic varieties with composition approaching a content of 60% acmite. However, aegarine augite of comparable composition is usually decidedly green in colour and is markedly pleochroic which is not the case with these crystals. The lack of pleochroism tends to indicate that the pyroxene may contain ferric ions and it may tentatively be suggested that the mineral owes its properties to the presence of both sodium and ferric ions in the pyroxene lattice.

In the Three Kings rock the pyroxene is found in association with haematite, rutile, and haematised pseudomorphs and partial replacements of olivine. It appears possible that, as a result of roasting in an oxidising atmosphere, olivine was caused to release magnesia and silica, original titanite and ilmenite made titania available to form the rutile, and that magnetite was oxidised to form haematite. The encrusting haematite may also have been derived from the reaction of ferric chloride and steam in the gaseous exhalations (Dana, 1946, p. 532). It may well be assumed that in so porous a body as a scoria cone a hot blast of escaping gases would be supplied with indrawn air and so produce oxidising conditions. Consequently ore minerals in the heated rock might well be the main source of the iron in the resultant haematite. Krauskopf (1957) has demonstrated on thermodynamic principles that, where the concentration of free oxygen exceeds  $10^{-15}$  (which he regards as a safe upper limit) in most magmatic gases at  $600^\circ\text{C}$ , then all iron present should be converted to haematite. The presence of rutile and the fusion of the basaltic rock show that temperatures in these local situations were undoubtedly in excess of this value. If it is valid to assume that atmospheric air is drawn in by the gaseous exhaust then the concentration of oxygen would also be expected to be much higher than that indicated above. Twenhofel (1927) found that while artificial magnetite inverted irreversibly to haematite at  $550^\circ\text{C}$ , natural magnetite did not do so until  $800^\circ\text{C}$ . Accessible magnetite in rock subject to roasting and in the presence of free oxygen as is here conceived would therefore expectably be converted to haematite. Lepp (1957), as a result of differential thermal studies, traced the oxidation of magnetite by heating in air, and showed that the reaction begins at  $375\text{--}400^\circ\text{C}$ , and proceeds in three steps with the final conversion beginning in the range  $550\text{--}570^\circ\text{C}$ .

The probability is that two processes in conjunction contributed to the mineralogy of these unusual rocks – changes induced by partial or complete fusion and oxidation of scoriaceous material bordering the passageways followed by escaping gases, and precipitation of a minor nature from the emanations themselves. In the heated rock ferrous iron is absorbed by the olivine and some magnesia and silica is lost; augite has taken up soda from the melt to form a sodic diopside which is also enriched with iron

in a ferric condition. The encrusting minerals lining vesicles in the rocks may in part be derived from volatiles in the heating gases or from volatiles distilled out of the heated rock. They would appear to have formed when temperatures were at a moderately low level for it is improbable that rutile and haematite could coexist under any conditions of elevated temperature (Segnit, 1953). While, therefore, high temperatures must be envisaged to permit the fusion of pre-existing rocks, and oxidising conditions to induce the formation of magnetite, the final deposition of volatiles may have occurred at more moderate temperature levels.

### *Dark Amber - Brown Pyroxene*

Pyroxene of this type was noted in the rock of a small mound (now removed) in the rifle range of the Auckland Grammar School built in an area of spatter cone activity on the surface of thick lava flows of Mt Eden. Lava appears to have been forced up through the cracks in the crust of the flow and to have intruded repeatedly into the mass of spatter materials constituting the knoll. Gases emanating from the thin intrusive sheets have fluxed and welded the scoriaceous rock and roasted basalt emplaced earlier in the structure. Along the margins of gas-ways permeating the mass, the bordering rock has been heat-altered so that olivines are largely haematized and plentiful rutile has been deposited.

The pyroxene is usually in small insets, commonly less than 0.2 mm in longest dimension. The smaller individuals have a dark amber colour, but the larger (and less numerous) phenocryst are pale brown to khaki in the centre with outer zones of varying width which are the same dark amber colour as the smaller crystals. Most are euhedral and many are twinned. Because of their small size, dense body colour and strong dispersion the determination of optic properties was somewhat difficult. The following data were obtained from pyroxenes in section No. 4437:

|                   |                                            |
|-------------------|--------------------------------------------|
| $2V_z = 60^\circ$ | $Z_{Ac} = 44^\circ$ — pale brownish kernel |
| 62°               | " " "                                      |
| 80°               | dark amber outer zone                      |
| 54°               | kernel                                     |
| 72°               | dark outer zone                            |
| 84°               | small dark individual.                     |

The dark variety was non pleochroic or, at most, very faintly so; dispersion strong.

In section 4380, dark amber pyroxene has been formed near vesicles or close to haematized olivine although the pyroxene of the remainder of the rock is almost colourless. The former mineral is set in a clear groundmass, conspicuously devoid of opaque granules and with feldspar and glass base. There seem to be little difference in optic properties between the two pyroxenes in this section. In both,  $2V_z$  ranges from  $56^\circ$  to  $60^\circ$ , and  $z_{Ac}$  is approximately  $40^\circ$ . For the Brown variety:  $\alpha = 1.704$ ;  $\gamma = 1.728$ .

According to the data of Hess (1949) these properties are consistent with those of a member of the diopside hedenbergite series in the ferrosalite range with Ca, Mg,  $Fe^{2+}$  ions in the proportion 50 : 20 : 30.

It is probable that the dark amber pyroxene of outer zones and individuals of section 4437, derives its colour and higher optic angles ( $2V = 72-84^\circ$ ) from the presence of ferric ions. Segnit (1953, p. 222) has shown that, in artificial pyroxenes, the presence of ferric oxide in diopsidic augite caused the optic angle to increase to about  $77^\circ$ . It would seem, therefore, that the roasting process, which induced alteration in the olivine to produce haematite and magnetite, caused either the ferrous iron of the existing pyroxene to be oxidised to a ferric condition or ferric oxide to be absorbed into developing pyroxene fabrics. Of these two alterations the latter would appeal as more probable.

### *Zeolites*

Minerals of the zeolite group occur as films lining vesicles but seldom in amounts that are optically determinable. In the rock of section No. 4968, a few of the vesicles are filled with a biaxial zeolite of positive sign that has straight extinction and is fast along in orientation. It tends to build up spherulitic masses of radiating fibres that have a nodular appearance reminiscent of balls of darning wool. This mineral is tentatively identifiable as natrolite.

From lava tunnels on the island of Rangitoto samples were obtained of a mineral encrusting scoriaceous lava and filling vesicles of rocks on the roof of the cavern. It occurs in aggregate bodies rather like those characteristic of prehnite. Its optic properties were determined as follows:

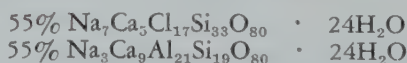
$$\left. \begin{array}{l} \alpha = 1.520 \\ \beta = 1.520 \\ \gamma = 1.527 \end{array} \right\} \pm 0.005$$

The mineral was positive,  $2V_z = 60-63^\circ$

$$r < v$$

Extinction straight. Cleavage in one direction.

The zeolite appears to be thomsonite with a composition, according to the data of Winchell (1951, p. 37), approximating to:



In both cases these zeolites could best be explained as secondary minerals produced by weathering assisted by percolating waters.

### *Feldspar*

The composition of microphenocrysts and microlites of plagioclase was determined by the methods of Nieuwenkamp (1948) and by measurements on the universal stage applied to the diagrams of Turner (1947). Agreement between compositions obtained by the two methods was reasonably close.

The results show that phenocrystic and microphenocrystic plagioclase is generally at least as calcic as basic labradorite and is frequently as calcic as bytownite. The range in composition shown by individuals in any one section is generally not great; compositions seldom vary more than 10-15% anorthite in any one rock. In very few examples did the plagioclase exhibit zonal structure; the laths were generally twinned according to the albite law often with the superposition of other twinning laws.

The following list shows typical examples:

| Section No. | Note             | Range in Plagioclase Composition   |
|-------------|------------------|------------------------------------|
| 5064        | Laths < 0.3 mm   | An <sub>50</sub> -An <sub>60</sub> |
| 4392        | Laths < 0.6 mm   | An <sub>65</sub> -An <sub>68</sub> |
| 4468        | .....            | An <sub>68</sub> -An <sub>80</sub> |
| 4393        | .....            | An <sub>50</sub> -An <sub>70</sub> |
| 4901        | Laths < 0.3 mm   | An <sub>53</sub>                   |
| 4921        | .....            | An <sub>70</sub> -An <sub>80</sub> |
| 4922        | biotite type     | An <sub>55</sub> -An <sub>70</sub> |
| 4377        | glassy variety   | An <sub>68</sub> -An <sub>75</sub> |
| 4401        | feldspathic type | An <sub>75</sub> -An <sub>83</sub> |

The feldspar of the groundmass is always very different in type, and, as already noted, is frequently of low r.i. and optically positive which suggests that it is often probably alkali-rich. Very generally the groundmass feldspar is cryptocrystalline.

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## THE GEOLOGY OF THE CAPE RODNEY - KAWAU DISTRICT, AUCKLAND

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### Summary

Five lithological groups overlain by Recent deposits are recognised. Otaian (Oligocene) sandstones and mudstones with associated andesitic agglomerates overlie argillaceous limestones of probable Bortonian (Eocene) age. These strata, with gently undulating or horizontal attitudes lap on to highly-sheared, siliceous claystones resting on a basement of deformed Mesozoic greywackes and argillites which contain interbedded spilites, chert bodies and ores of manganese, iron and copper. The interrelations and origin of the spilitic lavas, chert bodies and copper are discussed. The basement rocks have attained a grade of regional metamorphism equivalent to the chlorite-1 zone of the Otago Schists. The sequence is intruded and overlain locally by Pliocene Basalts.

### INTRODUCTION

The district described lies 25 miles north of Auckland, and comprises the mainland east of the Warkworth-Pakiri divide, together with off-shore islands (Fig. 1).

Hochstetter (1864) briefly described the Tertiary sandstones and basement rocks of Kawau Island which was later mapped by Hector (1869) who described the basement rocks ('Paleozoic Slaty Rocks'), the Tertiary sandstones and the rocks associated with a copper lode on its west coast. The first systematic geological description of the whole area was published by Cox (1881). Ferrar (1934) mapped the area and correlated the greywacke and argillites with the Waipapa Series of Bell and Clarke (1909) and the Tertiary sandstones with the Waitemata formation of Auckland City.

The great depth of weathering makes difficult interpretation of any but coastal outcrops and, because of the scarcity of fossils, mapping has been based on lithology.

The groups described are:

- |                                    |                                                                                      |
|------------------------------------|--------------------------------------------------------------------------------------|
| Waipapa Group:                     | greywacke sandstones and argillites.                                                 |
| Mangakahia Group:                  | highly sheared concretionary sandstones and mudstones.                               |
| Opahi Group:                       | hydraulic limestones, greatly sheared and fractured.                                 |
| Waitemata Group:                   | Waitemata Sandstone (sandstone and mudstone) and Manukau Breccia (andesitic debris). |
| Ti Point Group:                    | basalt flows, plugs, sills and dykes.                                                |
| Pleistocene and<br>Recent Deposits | } sands, muds and gravels.                                                           |

All groups are separated by marked unconformities. The basalts intrude and overlie the Waitemata Group but are overlain in turn by the deposits of the Pleistocene and Recent.

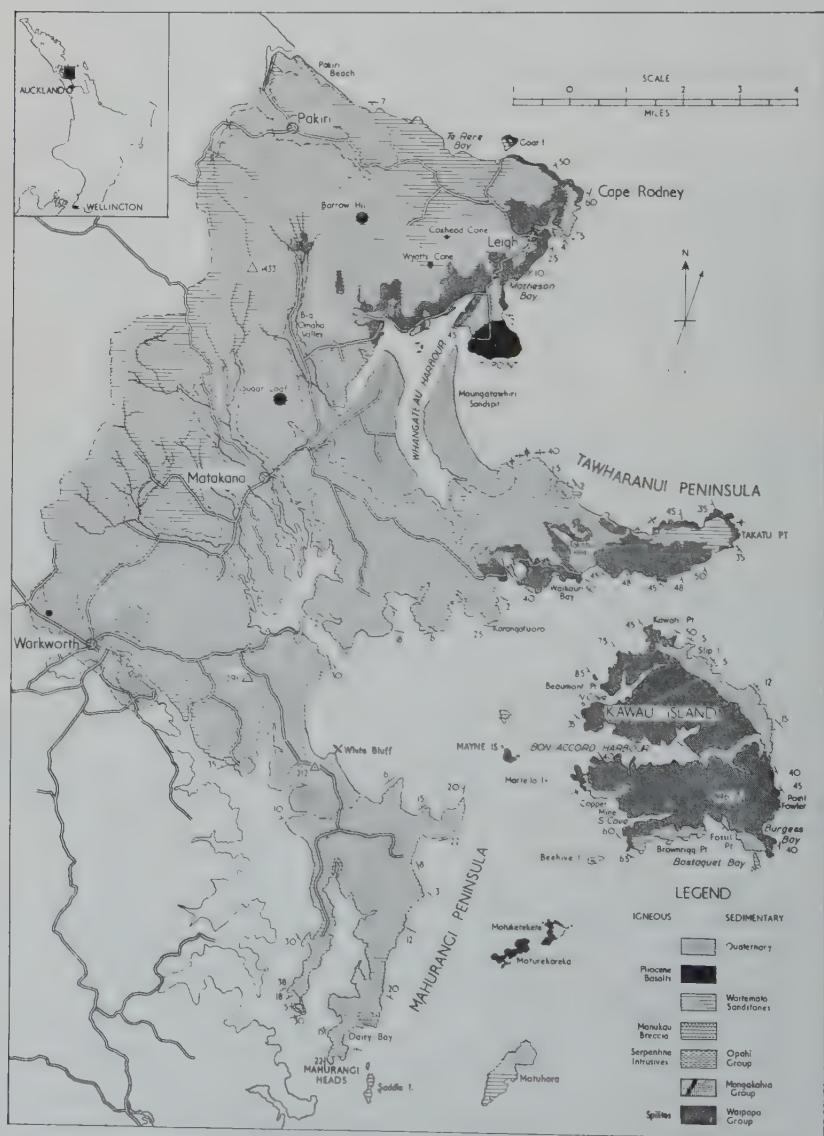


FIG. 1—Geological Map of Cape Rodney - Kawau.

## WAIPAPA GROUP

In this field, rocks of the Waipapa Group are chiefly dark grey argillites and strongly indurated grey and green greywacke sandstones, the latter, as a rule being highly silicified. The group includes red, brown and grey banded cherts and jaspillites, and also spilitic lavas with limestone lenses commonly associated with deposits of manganese oxide. Of lesser importance are grit beds, and igneous and intra-formational conglomerates. A thickness of approximately 8,500 ft was estimated for the group in this area.

Waipapa rocks are exposed in coastal sections between Tawharanui Peninsula and Cape Rodney and on Kawau Island. Elsewhere they are generally covered by younger formations. Their structure at Tawharanui Peninsula was discussed in an earlier paper (Hopgood, 1960) where it was shown that the major structure consists of an overturned anticline plunging at  $10^{\circ}$  north-west. Later folding produced minor corrugations with axes oblique to those of the larger fold and developed shear fractures. The corrugations plunge at angles of approximately  $45^{\circ}$  on a bearing between S.S.E. and South.

*Greywacke Sandstones*

Massive sandstones, ranging in colour from light grey-brown through greenish-brown to dark greenish-grey, are important members of the sequence. Bedding is either absent or indistinct and only where the texture is gritty, is grading of stratification evident. The beds are then seen to dip steeply to the south-west concordantly with the other strata of the group. Joints occur both as closely spaced cracks and as isolated wide fractures in which secondary deposition of quartz, chlorite, and occasionally epidote, has taken place. Three sets of joints, longitudinal, cross, and shear, were recognised in the field; shear planes persist for great distances. Where intense, shearing has formed zones of parallel planes separated by layers of brecciated sandstone cemented by secondary quartz and chlorite which show slickensides that indicate the direction of movement. As the shear zones are easily eroded, they tend to produce gaps several feet wide on shore platforms. Crush zones of green mylonite in lensoid masses resemble volcanic rocks but are distinguishable by their lighter colour.

Where spilitic lavas occur in the sequence, neighbouring sandstones acquire a distinctly green colour due to the introduction of chlorite. This change is so pronounced in places that the sandstones may easily be mistaken for lavas, especially in those areas with marked silicification of the country rock. The abundance of silica in the sandstone members contrasts strikingly with the extreme deficiency of this mineral in the argillites.

Breccias of dark argillite fragments in a sandstone matrix are present at several localities. These are interpreted as having been formed before consolidation by the scouring of turbidity currents flowing over soft semi-compacted muds so that the top layers were shattered, picked up and redeposited together with the sands carried by the current. The fragments, which range from 2 to 10 cm in length, sometimes show common alignment in planes parallel to the bedding, thus indicating the direction of current flow.

Thin sections show the sandstones to be composed of equant, angular detrital chips, 0.25–3 mm across, set in a matrix of similar but finer fragments. Most of the fragments are monomineralic, but rock chips are common. The growth of secondary quartz, chlorite and sericite has frequently altered the original boundaries of detrital grains. Fibrous chlorite replaces ferromagnesians and biotite, and is most abundant where it replaces chips of volcanic rocks. Leucoxene is abundant and both pyrite and magnetite are scattered throughout the matrix of the sandstones, and in fragments of lavas. Detrital quartz in sharply angular to slightly rounded grains, serrated and clouded by marginal solution, makes up between 50% and 60% of the total rock fragments present.

Detrital feldspars, subequal in amount to the quartz, are of two types. In one extinction angles vary from  $0^{\circ}$  to  $18^{\circ}$  indicating plagioclase with An content about 30%. In the other fresher looking individuals have small extinction angles and display polysynthetic twins in which the range of An content, as determined by the method of symmetrical extinction, varies from 0% to 15%. A zonary arrangement of dust-like inclusions parallel to crystal faces is common in feldspars which have been clouded by saussuritisation. Occasional large crystals of orthoclase and abundant authigenic white mica in fine shreds were also noted. In some sandstones, as observed by Brothers (1956), prehnite forms ramifying veins and clusters.

Constituent rock fragments are mostly limonite-stained sedimentary rocks, with greywacke sandstone more common than argillite. Fragments of igneous flow rocks are also fairly common; they have abundant leucoxene and magnetite and bright green chlorite replacing the groundmass. Ghost phenocrysts of feldspar can be recognised from original crystal outlines. Many were basaltic in character; others were porphyritic, altered andesites. In the least porphyritic lavas, reconstitution and silicification has developed a texture in which chlorite and quartz pseudomorphs after feldspar are scattered throughout a fine mosaic. In all rock fragments plagioclase feldspars have small extinction angles probably as a result of the replacement of calcic plagioclase by diagenetic albite. For this reason precise determination of original rock types is not possible. Chips of slate with strong alignment of bladed and rod-like minerals are also present.

Conglomerates were found in three localities on Kawau Island. One, on the coast east of Kawati Point, dips at  $47^{\circ}$ – $245^{\circ}$ , is 40 ft thick, and contains pebbles of spilitic lava as well as of sandstone and argillite. The matrix is a fine greenish mudstone which shows signs of having been sheared subsequent to consolidation. The other conglomerate bands, one 50 ft thick and the other is 25 ft thick, outcrop on the east coast north of Burgess Bay, and are about 100 yd apart. They resemble the Kawati conglomerate but contain silicified pebbles of basaltic rock in addition to the sedimentary rocks. Nevertheless it is probable that the Kawati conglomerate is the lateral extension of one or both of the bands.

Rocks recognised in the conglomerates included:

- (1) Spilites of the same type as occurs within the greywackes;
- (2) Volcanic rocks with trachytic texture;
- (3) Vesicular basalt similar in appearance to that of Ti Point;

- (4) Altered andesites: (a) with porphyritic structure, (b) showing strong flow banding;
- (5) Altered trachytic rock containing sodic plagioclases and iron ores;
- (6) Greywacke sandstone.

### *Argillites*

Argillites are mostly well-bedded. They range in colour from black to light grey with an occasional stratum of pale green. Beds are commonly 1 cm thick alternately fine and coarse. The beds are broken by numerous tiny normal and reverse faults. Scalloped bedding planes where minute load-casts have been preserved by later sediment covering the undulations are seen in many places and flow-casting is also common in many of the layers: the latter has been used as criterion in determining the order of deposition. These structures have shown that the sequence in part of the area is overturned and thus explains the fact that the beds are less sheared and deformed towards the east, although the dip is westwards.

Where greywacke beds alternate with the argillites, boudin-like lenses of sandstone have been developed by shearing stresses acting parallel or sub-parallel to bedding planes (Fig. 2). The argillites have yielded by plastic flow around the greywacke masses and have accommodated themselves to deformation by flexure rather than by fracture. Small symmetrical folds, of wavelengths ranging from a few inches to two or three feet, plunge obliquely to the general dip of the strata, and are cut by major high angle

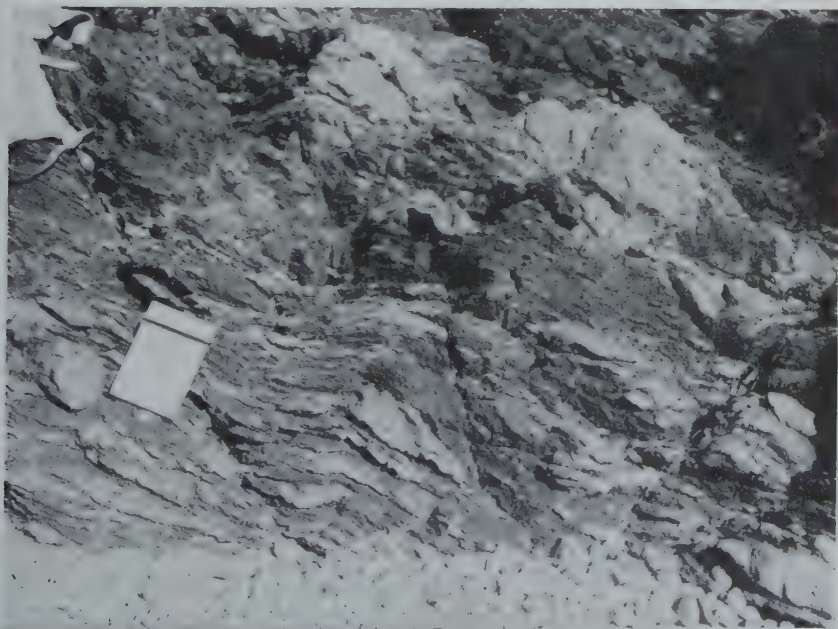


FIG. 2—Sheared ( $S_1$ ) alternating greywacke and argillite showing oblique shearing ( $S_2$ ) and corrugations (B), Tawharanui Peninsula.

shear planes which transect both rock types. It is suggested that movement on these shears was either rapid – allowing insufficient time for beds to adjust by plastic flow – or of great extent, thereby stretching the argillites beyond their elastic limit. Secondary minerals similar to those in the sandstones have been formed along and parallel to the planes of movement.

Thin-section examination shows that the argillites have the same constituents as the sandstones, but have achieved a more advanced state of reconstitution. Bedding planes are emphasised by a strong foliation resulting from the growth of sericite flakes. Quartz, feldspar and chlorite have also recrystallised from the matrix. Lensoid quartz mosaics form pods and minute corrugations at the intersections of shear planes with the bedding.

The greywacke sandstones and argillites are regarded as equivalent in grade to the Chlorite-1 sub-zone of Otago (Turner, 1938) in that they show a lack of cataclasis and of definite planar schistosity, but exhibit much reconstitution of the matrix, and saussuritisation and sericitisation of the feldspars. Brothers (1956) suggests that prehnite developed in preference to pumpellyite because reconstitution has taken place in sandstone lenses where shearing stress, hydrostatic pressure and possibly temperature would be low.

### *Spilitic Rocks*

The most important outcrops are immediately north of the copper mine and at Point Fowler on the east coast of Kawau Island. They occur also east of Waikauri Bay and at a small beach a mile east of Takatu Flats, Tawhara-nui Peninsula. The rocks which outcrop in lensoid masses intersected by numerous calcite veins are grey-green to leek-green in colour, fine in grain and extremely hard.

In some outcrops calcite occurs as pockets in the body of the rock and in others, as veins and lenses overlying them. At Point Fowler and at Waikauri Bay, in masses of pillows 30 ft thick (Fig. 3), individual pillows vary greatly in size from 3 ft in diameter to only an inch or two across; most are somewhat flattened.

At all other exposures spilites occur as narrow lenses and stringers of lava between bedding planes. They exhibit no pillow structures and probably are merely marginal tongues from larger masses. The lavas, although less shattered, show the same deformation as the sedimentary members.

In thin section the spilites are seen to be hyalopilitic in texture, with rare aggregates of plagioclase feldspar set in a groundmass of minute crystals of pyrite and small acicular laths of feldspar in random orientation. The phenocrysts are water-clear plagioclase, with a composition of 0–5% anorthite as determined on a universal stage from Turner's (1947) curves. Both normal and parallel twins are present in phenocrysts which average 0.75 mm in length and 0.2 mm in width. Incipient flow structure is apparent where minute laths of feldspar are arranged in sub-parallel groups. Minute vesicles are usually occupied by calcite amygdules or by chlorite while a few of the larger vesicles are completely filled by one or more large crystals of calcite. Some of the chlorite-filled vesicles are rimmed by a thin layer of crystalline quartz. Calcite veins are built of crystals on the walls

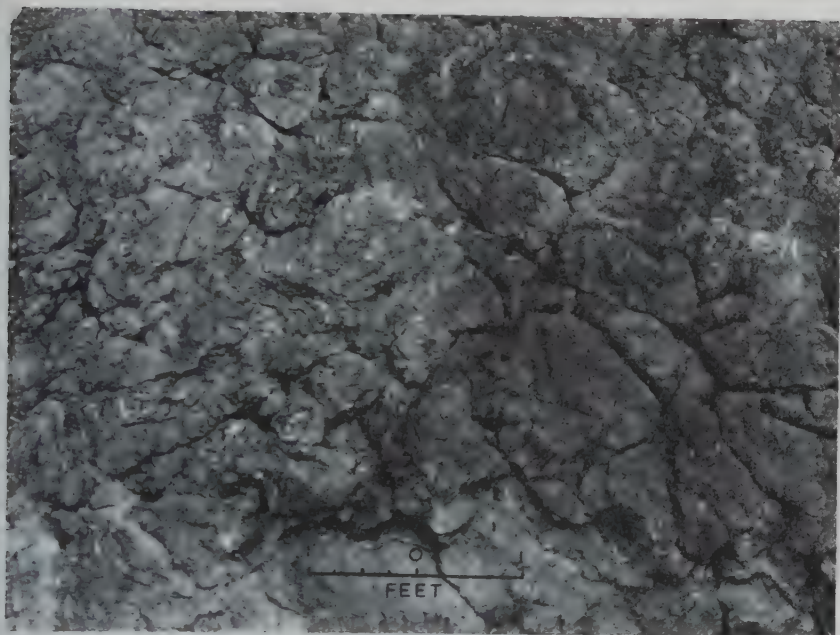


FIG. 3—Pillow Lava, Point Fowler, Kawau Island.

of fractures the central parts of the veins being filled by larger crystals aligned parallel to the vein walls. Some crystals, showing undulating extinction project into the vein at acute angles; this suggests that crystal growth has continued during movement along the fractures.

At Waikauri variolitic structures form a pisolitic type of skin on the pillows. The varioles are up to 5 mm across and have a concentric structure with an inner, dark sphere about half the diameter of the whole structure, a lighter-coloured, intermediate shell, and an outer, darker one. The darker areas are composed of glassy groundmass and brown cryptocrystalline pyroxene. Feldspar laths typical of the enclosing mesostasis have been included by the varioles. The lava itself is mottled with iron ore which has been excluded by the varioles. It would seem that the lavas were extruded as a fluid from which only iron ore and perhaps olivine had crystallised, and that feldspar crystallisation took place mainly after the variolitic texture had developed. After crystallisation of iron ore, and before separation of feldspar, minute segregations of pyroxene microlites accumulated around centres and grew outwards, thrusting aside the larger aggregates of iron ore. The varioles grew in three stages in the manner described by Buckley (1951, p. 501); i.e., following the growth and the segregation of the first microlites, the surrounding fluid was depleted "so that a metastable condition of slow growth" followed; later growth of a new concentric shell completed the structure.

The local lavas display most of the diagnostic features of the Spilitic Suite of Dewey and Flett (1911) in that they are variolitic in texture,

have a brown glassy base, and contain a little albite and pyroxene but lack olivine. They are similar in texture to those described from Waiheke by Halcrow (1956) and to the variolitic pillow lavas described by Wellman (1949) from the Red Rock Point, Wellington. Most other New Zealand spilites differ in that they are coarser in texture and contain pyroxene phenocrysts.

Some authors (e.g., Sundius, 1930) after consideration of the ratios An/Ab/Or have concluded that the existence of a primary spilitic magma is possible. Like Eskola (1935), Sundius (1930) suggests that there is also good evidence for albitisation, and concludes that spilites have a composite origin involving both primary and secondary processes. The frequent evidence for alteration in spilitic rocks is stressed by authors who favour hypothesis of secondary replacement of anorthite by albite (Eskola, 1935; Park, 1946).

In view of the freshness of albite phenocrysts, and indeed of the rocks as a whole, together with evidence of replacement afforded by vesicles infilling by calcite and chlorite, the writer is inclined to regard the Cape Rodney-Kawau lavas as having been affected by late magmatic metasomatism. Basic magma is postulated as experiencing a petrogenetic trend similar to that suggested by Turner and Verhoogen (1951, p. 210) in which crystal settling of early-formed olivine and, in the present instance, pyroxene (since this is rare in this field) took place. Extrusion of the residual magma followed, together with subsequent enrichment in soda as it came in contact with the comparatively soda-rich greywacke sediments, themselves saturated with sea water. A low temperature "stewing" of the extrusion in a sodic environment led to concomitant albitisation of feldspars, formation of chert and calcite, and ores of iron and manganese (Eskola, 1935; Park, 1946).

### *Banded Cherts and Jaspilites*

Siliceous rocks crop out on Kawau Island, on many of the small peninsulas in Bon Accord Harbour, and on the hill to the north-east; banded cherts are exposed on the shore platform at the old copper mine, at Beaumont Point (Fig. 4), and along the shores of North and South Coves. On the mainland, however, the only exposure of such rocks is in the headland east of Waikauri Bay.

East of Waikauri Bay, at the old copper mine and at Beaumont Point, spilites intrude the sequence, but at the other localities cherts are not seen to be associated with lavas. Nevertheless, it seems likely that lavas do accompany the cherts in all cases and that where not observed the lavas may be considered as merely obscured.

Cherts and jaspilites occur in bands of 1-3 in. in thickness making up composite bodies as much as 200 ft thick. They are generally brown or red but the colour may range from white to black through grey, yellow, orange, red and brown, depending on the content of iron oxide in the layers. The grey cherts are composed of pure cryptocrystalline silica and rare, minute particles of crystalline silica which possibly represent organic bodies. The bands are generally concordant with adjoining strata but discordant folds

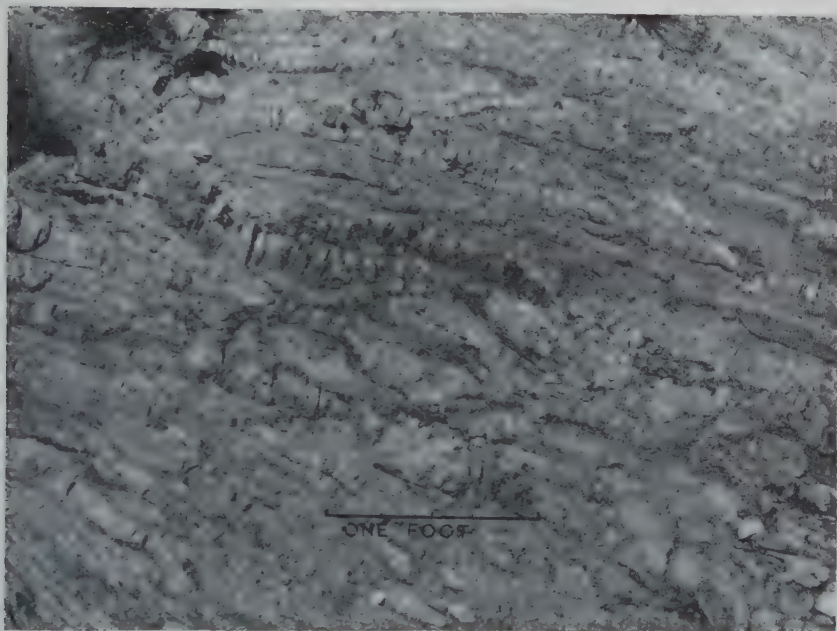


FIG. 4—Banded cherts. Beaumont Point, Kawau Island.

ten feet or more in amplitude may be seen. Bands within the chert bodies seldom exhibit the lensoid structures observable in sandstone and argillite members.

Manganese ores are associated at all localities, the manganese oxide occurring as a "bloom", or in small patches and veinlets, or in greater quantity. At Waikauri Bay the ore is an encrusting deposit an inch thick and at Beaumont Point forms large mamillary masses a foot or more across and several inches thick.

### *Mylonites*

At several localities crushed greywacke occurs in pale green lenses of slightly porous, but comparatively hard rock, which, although bearing some resemblance to spilitic lavas in the field, may be distinguished from these by its lighter colour and more open texture. It is possibly equivalent to the 'green mylonites' of Waiheke Island (Halcrow, 1956).

### *Origin of the Waipapa Group*

The rocks of the Waipapa Group are clearly of geosynclinal origin and the presence of interbedded volcanics suggests that they may be classified as typical eugeosynclinal deposits. Local variation in the rate of deposition is suggested by the presence of conglomerates and by great thicknesses of massive sandstones as at Kawau and Tawharanui. These features imply temporary shallowing of seas or proximity of land, causing the finer frac-

tion of redeposited sediments to bypass the area and be deposited nearer the axis of the geosyncline. The inclusion of spilite pebbles and greywacke in the conglomerate bands suggests operation of the "cannibalistic" process of Krynine (1948).

It would seem that the bulk of the Waipapa Group of sediments was deposited in the moderately deep waters of a late Palaeozoic or early Mesozoic mobile geosynclinal belt whose axis ran parallel to the present east coast of the North Auckland peninsula.

From their content it is concluded that the sediments of the Group have been derived from an igneous and metamorphic terrain. The strongest evidence for this lies in the nature of conglomerates (found at Great Barrier Island and elsewhere outside the area) which include granitic and other acidic igneous rocks. Pebbles in the Kawau conglomerates are commonly silicified volcanics with marked trachytic texture and are probably derived from terrestrial basalt flows. Some of the micro-breccias contain altered metamorphic rock fragments and chips of indeterminable silicified volcanic rock.

The dark colour of shales interstratified in New Zealand greywackes has been attributed by Broadgate (1916) to the presence of plant material, an opinion apparently endorsed by Brodie (1953). No definite plant fragments have been seen by the writer in the present area, although Mr D. Kear (pers. comm.) reports finding vegetable remains in slabs at Kawau. Brothers (1956), however, showed the carbon content of an argillite from Tawharanui to be negligible and suggested that the dark colouration was due to the high content of iron oxides (23.3%). This figure is abnormally high in comparison with the average percentages of Pettijohn (1949) of 4-6% ( $\text{FeO} + \text{Fe}_2\text{O}_3$ ) for shales.

Despite the view of writers (Benson, 1923; Wellman, 1952; Brodie, 1953; Halcrow, 1956), who postulate a western area of provenance for New Zealand Mesozoic greywacke it is suggested that the material of the local greywacke was derived from the east. The following evidence is cited in support of this view:

- (i) The conglomerates in greywackes of Great Barrier Island contain igneous boulders up to 18 in. in diameter (Bartrum, 1921) whereas igneous pebbles in the conglomerates at Kawau rarely exceed 2 in. in diameter.
- (ii) Seismic studies of the South Pacific by Officer (1955) show that the thickness of the crust along the East Cape-Kermadec-Tonga Ridge reaches 20-25 km, whereas west of New Zealand the thickness of the crust appears to be only 5 km, the same as that in the south-west Pacific basin. Officer therefore dismisses the possibility of there ever having been land in the area now occupied by the Tasman Sea.

The features shown by the spilites - fineness of grain, pillow structures and intimate association of sediments at the margins - all indicate that the lava was extremely fluid. Probably some of the lavas were extruded on the sea-floor whilst others were intruded into soft wet sediments below the floor. Additional evidence supporting the subaqueous emplacement of the flows is afforded by calcareous ooze and fine fossiliferous muds found between pillows.

The absence of baking in the adjacent sediments is possibly due to one or more of the following reasons: lack of sufficient heat in the lava to bake the sediments, which were saturated with, and surrounded by, cold seawater; poorly conducting glassy skins on individual pillows insulated the bodies; the greywacke sediments have since been strongly indurated so that visible effects of early baking would be difficult to detect.

### *The Origin of Cherts and Jaspilites*

The theories that have been advanced to explain the origin of silica and the manner of its deposition in such rocks are as follows:

(a) *Syngenetic Deposition*: Syngenetic deposition from organic remains implies partial solution of organic silica and its subsequent deposition as chert. Inorganic processes likely to produce cherts require the silica either to be in ionic solution, or as a sol, and until recently the idea of flocculation of a colloidal suspension was favoured by most authors. For example, Taliaferro (1933) regarded cherts as consolidated gels formed by loss of water. More recently Roy (1945), pointed out that earlier writers had accepted the experimental results of Kahlenberg and Lincoln (1896) who had erred in assuming a colloidal form for silica. Harman (1925-26-27), had earlier shown that silica existed in the ionic form  $\text{SiO}_3$ . Roy concluded that silica in natural waters existed as a solution or crystalloid rather than as a colloid and that the evidence, pointed to an ionic state. He also stressed that marked changes in pH are likely to cause changes in solubility.

Twenhofel (1950), considered that deposition of chert in shallow seas resulted where silica-bearing waters met the ions necessary to cause precipitation and concluded that "If chert and flint exist in rocks that were deposited far from mouths of streams, it seems best to postulate an origin other than syngenetic or refer the silica to magmatic derivation."

However, other authors (e.g., Ruedemann and Wilson, 1936) have postulated a deep-water origin of cherts because they are associated with geosynclinal sediments, spilitic lava and radiolaria. The cherts described by Ruedemann and Wilson are considered to be of primary origin as they occur in bands separated by thin shale partings - a combination unlikely to form as a result of secondary silicification.

(b) *Penecontemporaneous Deposition*: Theories of penecontemporaneous deposition postulate precipitation of silica along with normal sediments followed by solution and, through later concentration, re-deposition. In this way nodules and highly siliceous sediments might be explained but well-banded cherts with sharp boundaries against other rocks must owe their origin to some other cause.

(c) *Epigenetic Deposition*: Epigenetic deposition depends on waters circulating in the already consolidated rock to transport silica which is later precipitated in joints and along fault zones. Twenhofel (1950) doubts the feasibility of this process if applied to the zone of cementation below the water table but agrees that it is more likely to take place in the zone of weathering above. Red cherts of the south-west

Wellington district may well have originated in this way, and veins of silica throughout the greywacke sandstones of the present field are undoubtedly of epigenetic origin.

In assessing these different views with respect to the cherts and jaspillites of Kawau it would seem that a syngenetic origin is the most likely. It is favoured because of the sharp, rhythmical banding and the sharp horizontal contacts without gradation into the adjacent sediments. Furthermore, there is no evidence of replacement of original sedimentary features, nor is there an association with faults, with the possible exception of the occurrence at the old copper mine, where cherts form bands parallel to, but not within, a fault zone.

The association with lavas in most places seems to be more than coincidental. Park (1946) concluded that the jaspers associated with the spilites and basalts of Olympic Peninsula were the result of precipitation of silica during extrusion of lava and subsequent fumarolic activity. He suggested that solutions rich in silica would have been set free during the "stewing" of these lavas in hot aqueous solutions and primary zones whence albitisation took place. Eskola (1935) has shown that under these conditions anorthite is converted to albite. Siliceous solutions, on reaching the top of the flow, would begin to precipitate silica, according to Park.

Compared with the spilites of Olympic Peninsula, those of Tawharanui Peninsula are small in volume, and any fumarolic activity associated with them would probably have been slight. On the other hand, it is generally agreed that the solubility of silica in aqueous solution decreases with increase in pH. The writer suggests that with the extrusion of lava, carbon dioxide would be released in quantity and this would form carbonic acid, so that precipitation of the silica already present in sea water in the ionic form advocated by Roy (1945) would occur. Circulation of sea-water by convection would ensure a continuous supply of silica solution. Thus, release of silica solution from the lavas would not be entirely necessary. Periodic break-through of the lava from its glassy selvedge would cause intermittent release of carbon dioxide as new surfaces were exposed, and in this way the banding of the cherts would be explained.

A feature of the cherts east of Waikauri, is that iron staining is greatest adjacent to the lavas. Moore and Maynard (1929) found experimentally that on mixing iron and silica solutions, the iron and about half the silica were precipitated. In the case of the red cherts or jaspillites iron solutions were probably derived directly from the lava so that precipitation would have begun immediately the solutions mixed with sea-water. Overall decrease of iron oxide in the chert with increasing distance from the lavas is consistent with the mode of origin.

Manganese oxide encrustations on cherts and lavas at Kawau were in the past sufficiently abundant to be mined. Their mode of occurrence suggests, contrary to Park's (1946) theory, that this mineral has been deposited after all the others. It is possible that the encrustations are simply alteration products due to weathering of original manganese mineral contained in lavas.

*Copper:* The copper ores at Kawau Island occur in a crush zone striking at  $45^\circ$  and dipping at  $65^\circ$  towards  $135^\circ$  immediately south of a parallel

belt of banded jasperoid cherts at Copper Mine Point. The fault zone, from 6-15 ft wide (Ferrar, 1934), has been mined for a length of 400 ft, yielding ores containing an average of 16% copper. The sulphides and ores, are of the "red bed" type according to Henderson (1939), and include chalcopryrite and pyrite, with some bornite. They are similar to those at Maharahara and the Raukotere Basin near Gisborne and at Great Barrier Island. The lode is capped by gossan and manganese oxides underlain by lenses and irregular masses of pyrite and chalcopryrite; the surface of the lode is coated with a blue and green efflorescence of copper carbonates.

For purposes of comparison, the writer has visited the old workings at Great Barrier and Maharahara. At Great Barrier, the lode was similarly located in a crush zone (Bartrum, 1921) and appears to have been similar to that at Kawau. The only difference noted was the presence of veins of crystalline quartz at Great Barrier which, probably have arisen from subsequent andesite intrusions. At Maharahara the ore body is associated with cherts and jaspers (Lillie, 1953) and spilitic rock similar to that at Kawau (collected by the writer). Drilling at Kawau has revealed the presence of spilitic rocks close to the lode, as was expected from the occurrence of such boulders on the beach nearby.

An hypothesis suggesting sedimentary origin for the copper ores, as advanced for those of Arizona (Finch, 1935) and New Mexico (Lindgren, 1910), requires that the sediments should have been deposited at a time when a copper-bearing igneous terrain was being actively eroded. Although the possibility of sedimentary origin appears feasible it has been noted that the metal does not occur commonly in the greywackes which are notably fractured and faulted. Furthermore, should the copper be confined to one or two horizons then ore bodies would be expected parallel to the strike at the intersection of fault zones cutting these strata. This, however, is not the case and the idea of a sedimentary origin for the ore is consequently discarded.

If the ore were of later igneous origin, veins or intrusion cutting through the greywacke in the vicinity of the lode should be evident. No such veins exist. The possibility of a primary igneous origin, contemporaneous with enclosing sediments is supported by the presence of nearby spilitic lavas which contain copper.

If the copper was derived either from later intrusion or from coeval lavas, concentration of the ore would be necessary. Circulating underground waters, by solution would tend to carry soluble salts to the fissures or porous beds where redeposition could take place. Supergene enrichment would then occur after exposure to atmospheric weathering and the action of meteoric waters.

The fact that copper ore bodies are found at only one locality in the Cape Rodney-Kawau area may well be due to the fact that only at this place are the lavas cut by a fault zone along which the copper minerals could be concentrated and enriched. Similar conditions exist at Great Barrier.

The writer is of the opinion that the deposits of banded cherts, limestone, the iron and manganese ores, and the copper lode, are all genetically linked. The cherts are probably a precipitate largely from sea-water, but the manganese and iron oxides, calcite and copper are considered to have been derived directly from the spilitic lava.

### *Age and Correlation of the Waipapa Group*

Direct evidence of the age of the group in the Cape Rodney-Kawau area is lacking. The only fossil found, too crushed and leached to be of diagnostic value, shows a series of concentric ribs of asymmetrical cross-section and bears some resemblance to the species, *Inoceramus baasti* and *Maitaia trechmannii*, (Dr C. A. Fleming, pers. comm.; Milligan, 1959). Greywackes stretch with little interruption from Whangaroa in the north to the Hunuas, south of Cape Rodney, forming what may be regarded as a regional anticlinal area (Fleming, 1953). Permian fossils have been found in the beds at Whangaroa and the Triassic fossil *Hokonuaia* and Jurassic fossils (Milligan, 1959) have been found at localities south of Cape Rodney.

Too little is at present known of general structure to decide on structural or stratigraphical grounds whether the rocks of the Rodney-Kawau area are Permian, Triassic, or Jurassic in age. Some of the greywacke in the district is very similar to that of the Tokatea Hill and Moehau Series of Coromandel (Fraser and Adams, 1907) which underlie fossiliferous Jurassic greywacke. The writer is inclined to assign to at least some of the local rocks a Permian age; the less deformed bedded greywackes and argillites are regarded as possibly Triassic or Jurassic.

### *Mangakahia Group*

The term Mangakahia is adopted, following Hay (1952) for rocks with lithologic similarity to those formerly called Otamatea beds by Ferrar (1934).

The beds of the group are exposed in this region only in the central part of Mahurangi Peninsula. No fossils were found by the writer. On the west coast of the peninsula the rocks are sheared, fissile mudstones and siltstones, usually of dark grey colour. On the east coast strata are much lighter in colour and sandier, with occasional grit and pebble bands. Bedding, difficult to see except where pebble bands and brown limestone beds occur, is best exposed at White Bluffs and gives the impression of being disposed with extreme irregularity along a strike which averages approximately  $135^{\circ}$ . The rocks are fractured by fairly close-spaced joints which trend nearly parallel to the strike and following the line of the coast.

Conglomerates and grits are composed mainly of fragments of brown limestone and dark grey mudstone, together with smaller pieces of greywacke, set in a matrix of similar, but finer sandy material. The bands are only 5-6 in. thick and lens rapidly along the strike. Most of the sandstones are fairly even-grained and contain a small amount of glauconite. Concretions are rare and mostly found on the beach at the foot of siltstone cliffs from which they have weathered. They consist of hard, coarse sandstone cemented by calcite; the maximum diameter is about 4 ft. Associated with the concretions in the dark grey siltstones, is a yellow efflorescence that is similar to the melanterite replacing pyrite nodules found at Coverham which Wellman (1955) cites as evidence for correlating these beds with the Upper Cretaceous Whangai Shales of the North Island. None of the cone-in-cone barite concretions, so typical of the group elsewhere, were found, nor were

any of the following, which were regarded by Ferrar (1934) as characterising the Otamatea formation: septarian nodules, native copper, fragmental vegetal material, ammonites and *Inoceramus*.

If, as appears clearly in some places, the beds are nearly everywhere horizontal, a maximum thickness of rocks exposed above sea-level would be of the order of 200 ft. Contacts with other groups were not seen.

The lithologic features suggest deposition in a nearshore environment. The sandstones and mudstones were probably derived from a predominantly greywacke terrain. It seems likely that the source lay to the east since the Mangakahia Group attains its greatest thickness to the west in the Kaipara district where seas were presumably deeper offshore.

### *Opahi Group*

The name Opahi Group, proposed by Hay (1952) to replace Ferrar's (1934) Onerahi Beds, was originally intended to cover Bortonian claystones, argillaceous limestones, greensands and mudstones with flint lenses which outcrop in the Mangakahia Subdivision; it has been extended here to include rocks of the present district. The argillaceous limestone of the Warkworth district is included in the Opahi Group purely on grounds of lithological similarity as diagnostic faunas have not yet been found. Strata of the group outcrop over an area of approximately one square mile along the south side of Mahurangi Estuary, immediately below Warkworth. Another irregular outcrop of about two square miles, north of the township, has been intruded by a mass of serpentinite. The rocks are shattered off-white argillaceous limestones without visible bedding. Calcite veins in the rock suggest correlation with the "upper argillaceous limestone of Pahi" which contains lenses of crystalline limestone and is Whangaroan to Waitakian in age (Arlidge, 1955). Exposures are few so that neither upper nor lower boundaries were seen, nor could the thickness be estimated.

Weathering and alteration have obscured most of the original texture in the serpentinite so that the bulk of the rock is now composed of pale green fibres of chrysotile, bronze-coloured pseudomorphs of iddingsite and fibrous lamellar antigorite after olivine. Original fractures in the olivine crystals are represented by seams of magnetite and chromite.

The fine-grained and highly calcareous nature of the sediments suggests that the area of provenance was one of low relief and probably far removed from the area of deposition. Although part of the parent land may have been greywacke, the rocks of the Opahi Group were derived principally from a low-lying area of Mangakahia mudstones and claystones. The presence of cross-bedding in the Kaipara district (Arlidge, 1955) precludes the possibility of deep-water deposition, and a shallow, shelf sea environment is postulated during deposition of the Opahi Group.

### *Waitemata Group*

*Waitemata Sandstone and Maharangi Grit*: The nomenclature used here is in accordance with that of Ferrar (1934) and Brothers (1954a) and is applied to alternating unfossiliferous felspathic sandstones, ripple-marked mudstones, and carbonaceous shales, containing interbedded fossiliferous Mahurangi Grits, and basal conglomerates.

The formation, the most widespread in the Cape Rodney - Kawau district, is thickest to the west and thins laterally at Tawharanui Peninsula, Kawau Island and Cape Rodney. Close to Warkworth it overlaps on the argillaceous limestone of the Opahi Group but the nature of the contact with the Mangakahia group at Mahurangi Peninsula is not known.

Most of the sandstone layers are about a foot thick but many of the thicker layers measure up to 20 ft (Fig. 5). On the other hand, the mudstones and siltstones rarely exceed a few inches in thickness. Laminae of



FIG. 5—Typical sub-horizontal Waitemata Sandstone strata showing spheroidal weathering of coarse sandstones and grits, jointing and small-scale faulting. Part of the shore platform is visible in the foreground. Tawharanui Peninsula.

carbonaceous material, associated with fine shales and mudstones in many places, contain flakes and twigs crowded together in an indeterminate mass, too obscure to be useful in correlating. Roots are often preserved as thin calcite shells infilled with mudstone, and rocks containing these are invariably grey sandstones which probably represent leached soils. Wherever plant fragments are found, ripple marks are a common feature in adjacent beds and the ripple mark index,  $\lambda/a$  (Shrock, 1948) indicates that the sediments have been deposited from aqueous currents. Cobbles of white mudstone, included in the shale members of the group suggest erosion of local areas of Mangakahia rocks.

Basal members of the Waitemata Sandstone are notably different in lithology from the rest of the formation and comprise coarse conglomerate, block and pebble bands, green and yellow sandstones and impure lime-



perfectly formed crystals of 2 cm average length which, where they have originated from common centres form almost perfect rosettes.

Intercalated fossiliferous grit horizons throughout the lower part of the sequence could equally well be beds of Manukau Breccia. They are here considered as members of the Waitemata Sandstones because they are interbedded with the rest of the sequence but are distinct from the massive grits associated with the strongly disturbed sandstone and mudstone strata of the formation. These blue-grey beds, described as the Mahurangi Grits are composed of small andesitic lapilli containing pyroxene crystals up to 4 mm long, polyzoan fragments, pieces of small lamellibranchs and fragments of bone. Abundance of foraminifera, high glauconite content and presence of white mudstone fragments are also characteristic. Two closely similar grit horizons were noted but others may well have been unrecognised because of the lack of distinctive features. Grain size, the proportion of volcanic debris, fossil content and thickness of the beds increase towards the southern part of the area where Manukau Breccia is exposed.

The greatest height reached by the strata where the sequence is known to be uninterrupted, is 1,000 ft near Goat Island, Pakiri, where the dip is approximately  $5^{\circ}$ , so that the thickness is close to 1,000 ft. Although the base of the formation rises towards the east the attitude of the strata is generally close to horizontal and the whole sequence undulates gently, dipping in random directions from  $0$  to  $3^{\circ}$ . Exceptions to this are found in sections, locally tilted, where dips may be in excess of  $10^{\circ}$ . In the extremely contorted strata, associated with lenses of massive grits, or in those lying close to the basement, beds are often vertical or even overturned.

Such contorted strata occur close to the greywacke basement at Karangatuoro, on the south side of Tawharanui, where they are associated with basal conglomerate, on the north coast of the peninsula, and at Kawau Island (Fig. 7). Contortions adjacent to coarse massive grits are exposed on the west side of Ti Point. In all cases where such beds are near conglomerates the attitude of the plications shows that they have slumped away from the ancient coast. Tilted beds also dip off the old Miocene shoreline at Bostaquet Bay, Kawau; they form recumbent folds overturned in the direction of slump, thus indicating the direction of the ancient shoreline.

Pre-consolidational slumping in beds adjacent to grits took place where the latter were deposited on a sloping sea floor. Large volumes of ash and sand, travelling across the sea floor, gouged into, and ploughed up, the still plastic sediments, rucking them into characteristic sharp folds and convolutions. Brothers (1954a) has suggested that the Parnell and other grits of Auckland City were derived similarly from volcanoes on the site of Waitakere Hills. Primary dips are due either to compaction of the strata after deposition, or to the slope of the initial sea floor. Where the initial slope was steep, slumping of unconsolidated sediments took place until stable equilibrium was reached at angles of rest no steeper than about  $5^{\circ}$ . Angular unconformities are common between groups of strata and in many cases are due to the prevalence of subaqueous slumping in the unconsolidated strata. Several fine examples are exposed in the north side of Tawharanui Peninsula. Current bedding is more common in the coarser massive sandstones but occasionally is seen in the thinner, finer beds.



FIG. 7—Slump structures in Waitemata Sandstones. Kawau Island.

Minor faulting resulting from adjustment of unconsolidated sediments to stresses during compaction is common in all members of the formation. Cross-faulting formed by intersection of faults dipping at about  $60^\circ$  results from readjustment of beds that have moved laterally in response to tension of compression. Segments were thus enabled to move up or down to adjust to the change in area of the strata. Along the larger fault planes, drag has caused bending of the severed ends of the strata and it is along these faults that most of the small springs and seepages occur. Although faulting on a minor scale is common, the total resultant displacement is negligible since distinctive bands may be followed for some distance through several different fault segments.

*Manukau Breccia:* The writer has followed Ferrar (1934) and Brothers (1954b) in the use of the name Manukau Breccia to include andesitic breccias and conglomerates similar to those of the Waitakere Hills west of Auckland. The only two exposures of rock of this formation are at Mahaurangi North Head. On the west side of the head there is a 15-ft stratum of cobbles of andesite, limestone and dolerite, and of an anorthite-bearing volcanic rock. This bed is correlated with andesitic breccia north of Dairy Bay on the east.

Rounding of many of the cobbles suggests that they have been transported, or subjected to rolling on a shallow sea floor. An alternative and preferred hypothesis is that the material has been caught up from a deposit

of Albany Conglomerates (Bartrum, 1920b) during eruption. This would explain not only the presence of doleritic rock amongst predominantly andesitic material but also the rounded form of the cobbles, as well as the presence of pebbles of porphyritic rock with some flow structure. The porphyritic rock is similar to an andesite but composed almost entirely of plagioclase with subsidiary iron ore and small brown patches of a pleochroic cryptocrystalline mineral. The composition of the plagioclase phenocrysts ranges from An 88–90% to An 78–82%. The limestone fragments are very similar to some from the Motatau Group (Hay, 1952) and may have been derived from this source. Blocks of similar limestone associated with andesitic debris at Whangaparaoa and Motuhora have been described by Turner (1928) but these are of much greater size than the cobbles (2–3 in. diameter) of Mahurangi Peninsula.

The blocks of andesite in the eastern exposure contain well-formed radially-infilled calcareous amygdules up to  $\frac{1}{4}$  in. across. Blocks of andesitic breccia up to 4 ft across are common, and the whole represents a true volcanic agglomerate grading laterally, by decrease in size, into the Mahurangi Grits.

*Origin of the Waitemata Group:* The area supplying the detritus of the Waitemata Sandstone comprised Opahi, Mangakahia and Waipapa rocks, since fragments of all these have been found incorporated in the strata close to the contacts. The writer agrees with Turner and Bartrum (1929) that the region of provenance lay to the north-west and considers that a large proportion of the sediments was derived from land distributed much as it is at present. The Mahurangi Grits are considered to be derived from the same source as the Manukau Breccia. The size and angularity of blocks on Mahurangi Peninsula and Motuhora Island indicate clearly that the source of the breccia was located nearby. Either erosion has removed a volcanic edifice extending between the above localities, or else there was little or no cone-formation associated with eruption. Other centres of eruption have been located close to Whangaparaoa Peninsula to the south (Turner, 1928) and at Maitaia Peninsula on the Kaipara (Ferrar, 1934).

That the sediments and pyroclastics of the Waitemata Group were deposited in shallow seas is shown by the presence of carbonaceous shales, plant fragments and pieces of carbonised wood, and by ripple marks, current bedding, and intraformational conglomerates.

Turner and Bartrum (1929) considered that the current-bedding and shallowness of water is indicative of a deltaic environment in which sands and muds were deposited. The writer concludes that the Waitemata Sandstones were laid down in an environment which was partly transitional and partly neritic, in a region similar to the present Hauraki Gulf at a time when vulcanicity was widespread. Intermittent downsinking caused local changes in environment and facies. Although andesitic tuffaceous material was widely distributed at the time, subsequent erosion removed nearly all traces of the centres of the eruption.

*Age and Correlation:* Fauna from the basal beds and the higher Mahurangi Grits of the Cape-Rodney–Kawau District strongly suggest an Otaian age but in view of the general lack of age-determinative faunas, correlation of the strata with rocks outside the Auckland district is premature at present.

The following assemblage has been determined by Mr Hornibrook of the Geological Survey:

Sample N 34/505:

|                             |                                        |
|-----------------------------|----------------------------------------|
| <i>Calcarina mackayi</i> ,  | <i>Eponides repandus</i> ,             |
| <i>Cibicides perforatus</i> | <i>Cassidulina</i> aff. <i>arata</i> , |
| <i>Vaginula recta</i> ,     | <i>Notorotalia</i> n. sp.              |
| <i>Buninga creeki</i> ,     | <i>Glomospira</i> sp.                  |

### *Ti Point Group*

Basalts cut through the Waitemata Group in several localities but the only large extrusion is at Ti Point, south of Cape Rodney. Other outcrops are in four conical hillocks, a dyke and a sill. The Ti Point basalt flow has a general westerly slope away from the east coast where the vent was probably located. The rock, seamed by irregular layers of vesicles is unusually light in colour for a basalt, and is remarkably like that of Stony Batter, Waiheke (Halcrow, 1956).

The typical rock is a vesicular olivine basalt with marked trachytic texture. Large idiomorphic crystals of olivine are set in a finely holocrystalline groundmass of feldspar laths and tiny augites. A few small irregular phenocrysts of augite are present. The extinction angles of the groundmass feldspar laths are high, ranging between  $30^{\circ}$  and  $40^{\circ}$ , and determinations made from sections cut normal to (010) show the composition to be that of labradorite. The olivines generally have yellow edges due to deuteric alteration to iddingsite, and brown haematite stains along the fractures. The groundmass is sprinkled with small flecks of magnetite.

A narrow dyke which cuts through the middle of Goat Island at Cape Rodney has a similar composition and texture to the basalt of Ti Point but less pronounced flow structure. The Sugar Loaf, Barrow Hill and two conical hills in Wyatt's and Coxhead Creek valleys are formed of considerably darker basalt. A 10 ft thick sill of amygdaloidal basalt is exposed in a quarry at the head of Big Omaha Valley. This sill, or offshoots from it, is undoubtedly responsible for the presence of numerous boulders in neighbouring gullies. These basalts are characterised by the high anorthite content (80-90%) of the plagioclase feldspars and by the clots of clinopyroxene and olivine (about 2 mm diameter), which impart to the hand specimen a dark grey mottled effect.

The Sugar Loaf basalt is porphyritic in texture and contains large glomeroporphyritic clots of augite set in a groundmass of plagioclase feldspar, fine pyroxene crystals and minute flecks and rods of magnetite. Moderately large phenocrysts of zoned plagioclase are common and these have an anorthite content of 83-85%, determined by Turner's (1947) method. Rarely, small irregular crystals of olivine are present. The groups of large pyroxene phenocrysts show marked undulose extinction evidently due to strain set up during the final more viscous stages of the emplacement of the basalt.

The texture of the Barrow Hill basalt is intergranular to trachytic. Moderately large phenocrysts of augite and olivine set in a groundmass of

plagioclase laths and small pyroxene crystals, have corroded edges and are marginally altered to iddingsite. This rock is intermediate in texture between the basalt from Ti Point and that from the Sugar Loaf.

The sill at Big Omaha Valley is porphyritic in texture and is very similar to the Sugar Loaf basalt. Remarkably symmetrical arrangements of four or more large augite crystals ( $2V_z = 50^\circ$ ) in the form of a cross are common in thin-section, the crystals being twinned with composition plane parallel to (100). Olivine is lacking in this basalt, except for one extremely altered phenocryst. Amygdules are present along the contacts with the adjacent Waitemata Sandstone.

Residual boulders exposed now in open paddocks are strongly fluted (Fig. 8). The lapiez and solution pits are similar to those described by Bartrum and Mason (1948) from Hokianga and by Halcrow (1956) but



FIG. 8—Fluting in basalt. Ti Point.

probably at an earlier stage of development. Solution of the rock is ascribed to acid solutions dripping from mosses and epiphytes in trees of surrounding bush.

Since the basalts baked sediments of the Waitemata Group, and have evidently flowed over a topography eroded in them at Ti Point, they are probably Pliocene in age.

#### *Pleistocene and Recent Sediments*

The Flandrian Transgression resulted in a considerable accumulation of estuarine sands and muds in the Cape-Rodney – Kawau district.

Ferrar (1934) relegated a small patch of weathered conglomerate at the south-west end of Whangateau Harbour to his Pliocene Purua Beds but the present writer regards this as Pleistocene and correlates it with the formation of the 15-25 ft erosion surface of Brothers (1954). A surface of the same height is also found at Matheson Bay. Banks of fixed sand with gently seaward sloping surfaces at 8-12 ft. and interpreted as formed during the Flandrian maximum, are preserved in inlets of Kawau Island and on the south side of Tawharanui Peninsula. Fixed sands along the north side of Tawharanui Peninsula and at the west side of Whangateau Harbour are also probably late Pleistocene in age.

Above present high water mark modern shell deposits occur near the end of Takatu Point and at Fossil Point, Kawau. Drifting sands mark the north coast of Tawharanui, Maungatawhiri sandspit, and Pakiri Beach, while boulder beaches occupy heads of inlets in greywacke at Cape Rodney, Tawharanui and Kawau are replaced by gravel beaches in sheltered water such as Bon Accord Harbour. Blocks and slabs cover the short platform of the less exposed beaches eroded in Waitemata Sandstones but on the more open beaches, sands have accumulated. Throughout the area mud flats and mangrove swamps are common, notably those at Takatu Flats and Christian Bay. The valleys of the larger streams are mantled by alluvium accumulated in modern times.

### *Outline of the Geological History of the Area*

During the Upper Paleozoic a steep granitic and metamorphic terrain is postulated as having lain east of Auckland Peninsula. The climate of this ancient land was sufficiently mild, at least in part, to support vegetation and off its western coast the sediments of the Waipapa Group accumulated in a rapidly sinking trough; fluctuation of the rate of downsinking of the geosyncline caused lateral shift of the main axis of deposition, thus introducing lithological variation in the sequence. Short periods of still-stand are marked by the presence of sandstone layers interbedded with finer, darker argillites desposited when erosion was reduced and plant growth was better established. Renewed uplift is marked by the thick sequence of coarse marine sandstones.

From time to time, and probably early in the history of the geosynclinal cycle, lavas were extruded on to the sea floor and these initiated the deposition of thick, banded cherts. During orogenies when there was shallowing of the trough subaerial outpourings of basalts and andesites took place and provided a source of rock chips in the grits and pebbles in the conglomerates.

Towards the end of the Mesozoic, uplift of the basin began, and was followed by the onset of compression from the west which continued intermittently up to Tertiary times. Beds were folded into steep isoclinal folds which ultimately became overturned. A second set of folds - the B-corrugations - arose in response to oblique shear, when flexural slip ceased after bedding-plane shear became inoperative because of the closely appressed nature of the major folds.

The newly raised greywacke land was eroded and later deposition took place in a shallow basin formed further towards west. Gradual rise in sea

level occurred during the Upper Cretaceous along with uplifts and down-sinkings of the land during which the Piripauan Mangakahia Group, the Opahai Group and finally, in Tertiary times, the Waitemata Group were laid down.

The continued compression from the west after uplift of the Opahi Group resulted in further deformation of the greywacke and shearing of the Mangakahia and Opahi Groups in late Cretaceous times. At this time serpentinites were intruded into the argillaceous limestones of the Opahi Group.

Downsinking of the land and contemporaneous erosion of the sediments of all three of the above groups, contributed to the sediments of the Waitemata Group. Soon after submergence set in, submarine and subaerial andesitic eruptions began and these continued intermittently until the close of Southland time.

In the Upper Miocene, uplift again took place and the strata of the Waitemata Group were eroded. The Miocene covering strata were uplifted on a series of greywacke fault blocks at the time of the late Pliocene Kaikoura Orogeny and this resulted in marked difference in trend between structures on Tawharanui Peninsula and Kawau Island. Following this the basalts of Ti Point were extruded and this outpouring was followed by the injection of basaltic sills, dykes and plugs.

Present topographic features are largely the result of oscillatory movements of the sea during subsequent glacial and interglacial periods of the Pleistocene when changes of sea-level were recorded by extensive terraces around the coast. However, Recent erosion has left clear traces of only two of these oscillations — that responsible for the 15-25 ft terrace and the Flandrian maximum.

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## URUROAN BEDS OF THE HETHERINGTON INLIER, WEST AUCKLAND

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### Summary

The Pongawhakatiki Siltstone (new formation) with three coarser members, is exposed in the Hetherington Inlier. Small specimens of *Pseudacella marshalli*, which are believed to be within at least the lower part of the stratigraphic range of the normal-sized specimens, are exposed below *Torastarte bensoni* and *Lopha* cf. *haidingeriana*, and thus show the latter fossils to be locally of Ururoan age.

The association of *T. bensoni* with normal-sized *P. marshalli* in a conglomerate grit at Heale Ridge, Hokonui Hills, Southland, is described in an appendix by Mr I. G. Speden.

### INTRODUCTION

Jurassic rocks of the Pongawhakatiki Siltstone formation are exposed as the Hetherington Inlier to the south of Hetherington Road, Ruawaro (12 miles west of Huntly, Fig. 1, 2, 3). An interesting fauna, including *Torastarte bensoni* Marwick, has been recorded from there by Fleming (1953, 1957). In the course of a detailed geolgocial survey covering the topographic sheet N.Z.M.S. 1 N55, the present author obtained new stratigraphic data that were not known at the time of Fleming's papers. The present paper is published to introduce the Pongawhakatiki Formation, to record the overlapping ranges of *T. bensoni* and *Pseudacella marshalli* (Trechmann), to note the Ururoan (lower Jurassic) age of the oyster *Lopha* cf. *haidingeriana* (Emmrich) at Hetherington Road, and to present evidence regarding the range of small specimens of *P. marshalli*.

### STRATIGRAPHY

#### *Pongawhakatiki Siltstone (New Formation)*

Siltstone, with minor coarser members (Kouratahi Sandstone, 400 ft;  
Hetherington Conglomerate, 50 ft; and Ruawaro Sandstone, 50 ft) 5,500 ft

#### *Name and Type Locality*

Siltstones, with some coarser beds, are exposed in the Hetherington Inlier. They comprise part of a previously unnamed, thick siltstone formation which is well exposed to the south near Pongawhakatiki Trigonometrical Station (1,020 ft, Fig. 2). The formation is thus named the Pongawhakatiki

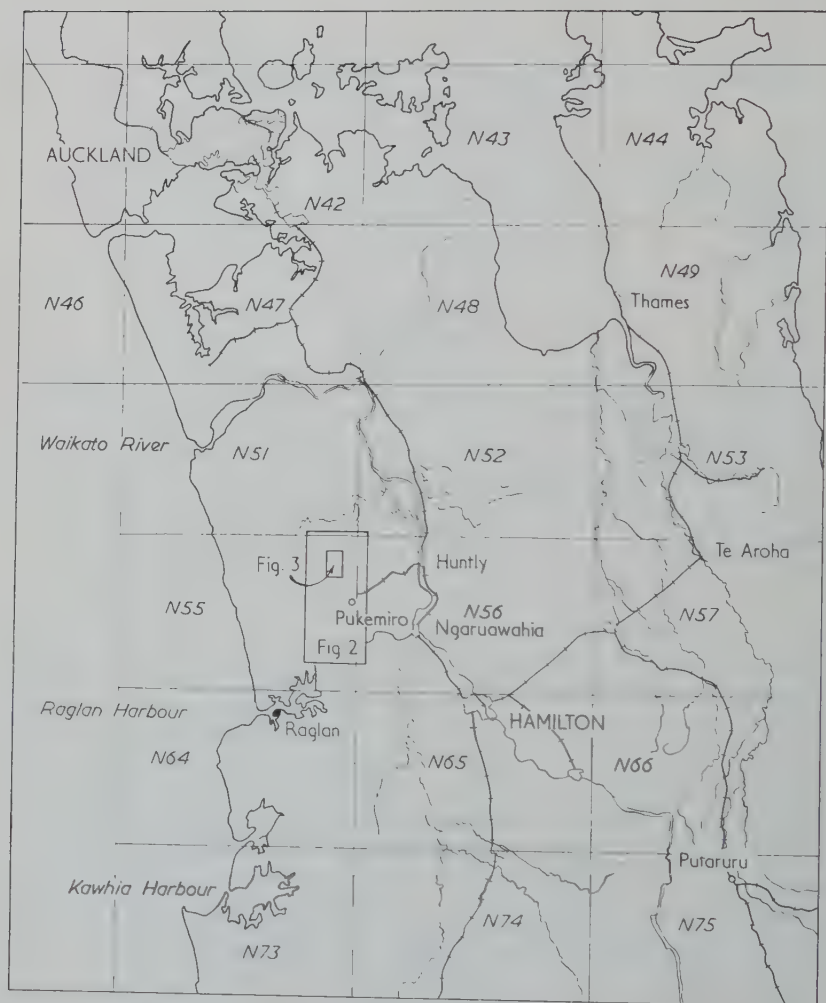


FIG. 1—Locality map.

Siltstone. The type section is selected in the headwaters of Ohautira Stream (Fig. 2), and extends from 30 ch north-east (N56/558559) to 110 ch south (N55/543570) of Pongawhakatiki. It includes the following beds:

*Overlying:* Conglomerates and sandstones with *Meleagrinella* aff. *echinata* (Smith) and belemnites.

# KEAR - URUROAN BEDS OF HETHERINGTON INLIER

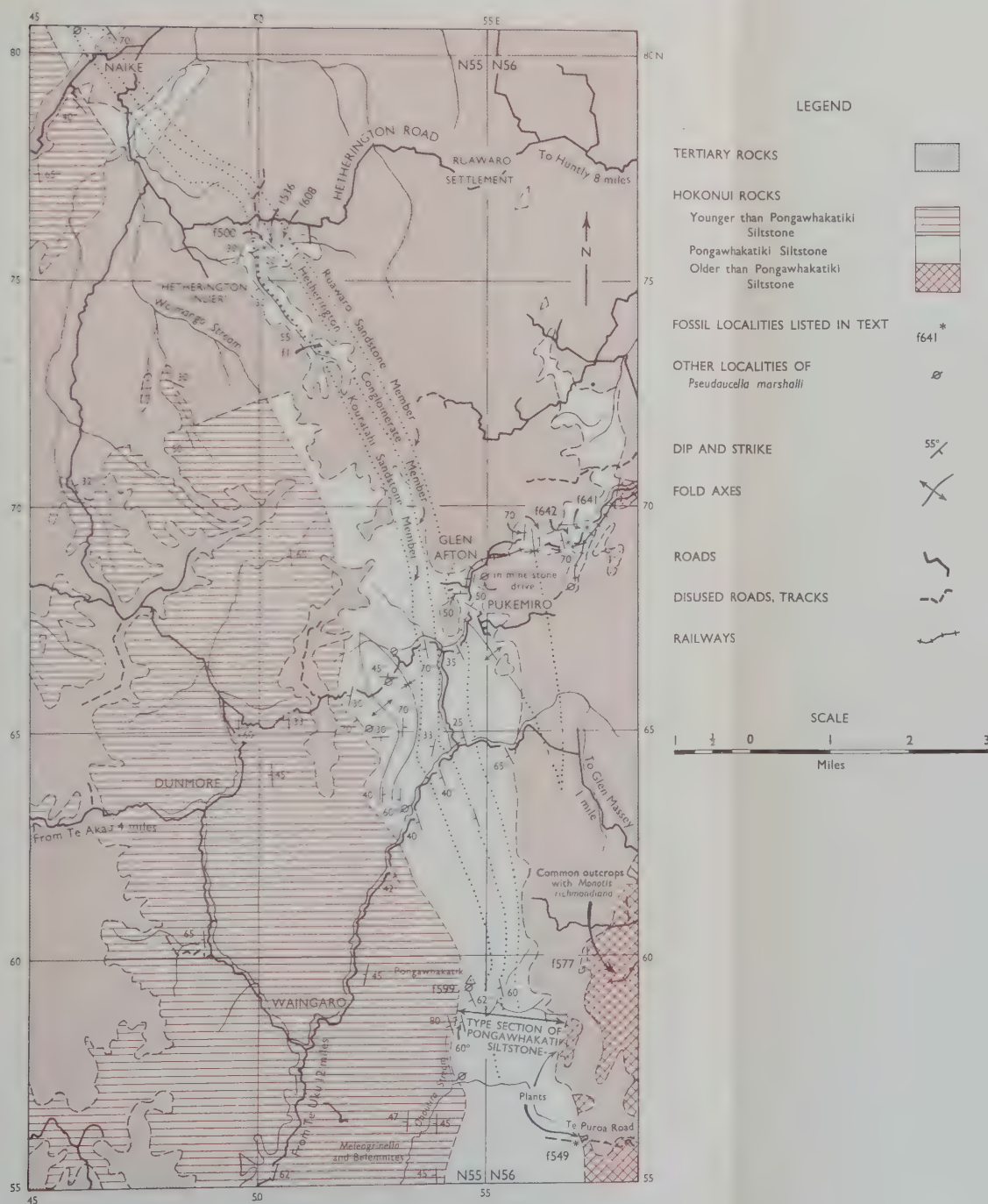


FIG. 2—Relation of Hetherington Inlier to other occurrences of the Pongawhakati Siltstone, including its type section.

# KEAR - URUROAN BEDS OF HETHERINGTON INLIER

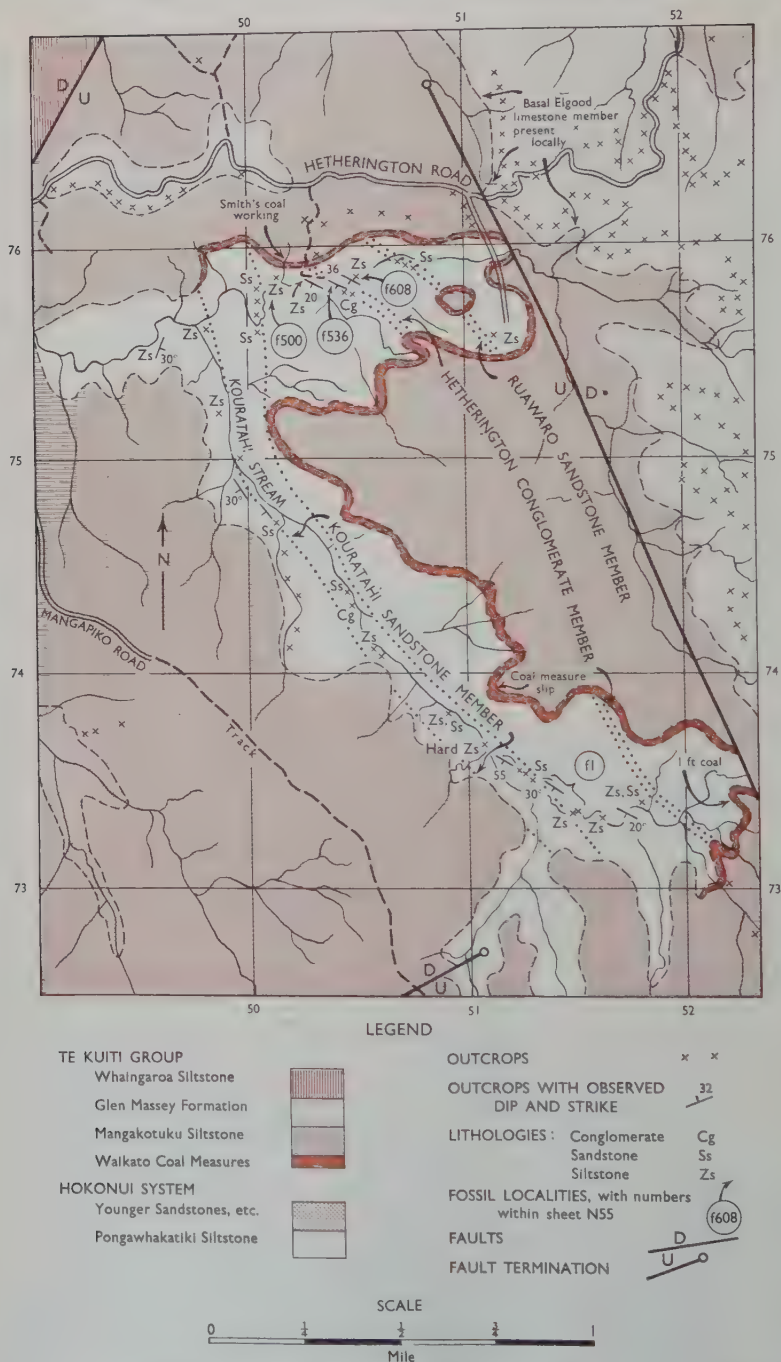


FIG. 3—Hetherington Inlier showing the mapped occurrences of the Pongawhakatiki Siltstone and its constituent coarser members.

*Pongawhakatiki Siltstone*

|        |                                                                                                                      |       |       |       |                    |
|--------|----------------------------------------------------------------------------------------------------------------------|-------|-------|-------|--------------------|
| (a9)   | Siltstone, with fine sandstone beds in upper part<br>(Pongawhakatiki itself is roughly 1,000 ft down<br>in this bed) | ..... | ..... | ..... | <i>Ft</i><br>1,500 |
| (a8)   | Siltstone, with occasional hard siliceous beds,<br>especially in lower part                                          | ..... | ..... | ..... | 1,250              |
| (a7)   | Interbedded siltstone and sandy siltstone                                                                            |       |       |       | 1,000              |
| (a6)   | Massive siltstone poorly exposed at base                                                                             |       |       |       | 1,500              |
| (a1-5) | Basal sandstone and conglomerate very poorly<br>exposed                                                              | ..... | ..... | ..... | 250                |

*Underlying:* Poorly exposed unfossiliferous sandstone.

The basal beds are poorly exposed at the type section, but crop out in Te Puroa Road cuttings to the south (Fig. 2) where they comprise:

*Pongawhakatiki Siltstone*

|      |                                                                                                                    |       |       |       |                  |
|------|--------------------------------------------------------------------------------------------------------------------|-------|-------|-------|------------------|
| (a5) | Weathered brown fine-medium sandstone, coarsest<br>towards base                                                    | ..... | ..... | ..... | <i>Ft</i><br>200 |
| (a4) | Weathered brown, white and pink sandstone with some<br>siltstone beds at top, and greenish pebbles towards<br>base | ..... | ..... | ..... | 8                |
| (a3) | Weathered conglomerate with greenish pebbles and<br><i>P. marshalli</i>                                            | ..... | ..... | ..... | 10               |
| (a2) | Weathered banded medium-coarse sandstone with <i>P.</i><br><i>marshalli</i>                                        | ..... | ..... | ..... | 6                |
| (a1) | Unseen                                                                                                             | ..... | ..... | ..... | 20               |

*Underlying:* Iron-stained weathered siltstone ..... 30

Brown sandstone with leaf impressions and carbonaceous  
material throughout ..... 50

No fossils diagnostic of age down to *Monotis rich-*  
*mondiana* Zittel, 2,000 ft below.

The Pongawhakatiki Siltstone, although not previously named, has been mapped as "Lower Jurassic Beds" by Henderson and Grange (1926, pp. 32-3) and as "Mesozoic" by Penseler (1930, pp. 132-3).

*Hetherington Inlier Sequence and Constituent Members*

The following 2,000 ft beds of the Pongawhakatiki Siltstone are exposed in the Hetherington Inlier:

|                                                                                                                                                                    | Ft       |
|--------------------------------------------------------------------------------------------------------------------------------------------------------------------|----------|
| (b7) Siltstone, poorly exposed .....                                                                                                                               | 500      |
| (b6) <i>Kouratahi Sandstone Member</i>                                                                                                                             |          |
| Sandstone (coarser and with fine conglomerate at base), with thick siltstone beds .....                                                                            | 400      |
| (b5) Siltstone sandy in part, with common <i>P. marshalli</i> (N55/f1, f500) .....                                                                                 | 300      |
| (b4) <i>Hetherington Conglomerate Member</i>                                                                                                                       |          |
| Interbedded conglomerate (volcanic pebbles to $\frac{3}{8}$ in., angular siltstone cobbles) with fossils, <i>T. bensoni</i> , etc. (N55/f536), and siltstone ..... | 50       |
| (b3) Indurated siltstone with small <i>P. marshalli</i> (N/55/f608) 100 ft down .....                                                                              | 300      |
| (b2) <i>Ruawaro Sandstone Member</i>                                                                                                                               |          |
| Coarse sandstone .....                                                                                                                                             | 50       |
| (b1) Siltstone .....                                                                                                                                               | 400 plus |

The three coarse constituent members have their type localities within the inlier in the tributary of Kouratahi Stream which flows westwards  $\frac{1}{4}$  mile south of Hetherington Road (Fig. 3). The Kouratahi Sandstone Member (named from Kouratahi Stream) is well exposed in a waterfall, 13 ch east of the junction of tributary and stream; the Hetherington Conglomerate Member (named after Hetherington Road) is exposed in and near a minor gorge, 30 ch east of the junction; and the Ruawaro Sandstone Member (named after Ruawaro Settlement) crops out to the south-east of the stream, 45 ch east of the junction. These three constituent members can be traced with decreasing certainty southwards beyond the Hetherington Inlier (Fig. 2).

An estimated 1,300 ft of beds are obscured by Tertiary rocks to the west of the inlier up to the base of the thick overlying sandstone formation (Figs 2, 3).

### *Tertiary*

The Tertiary formational names of the legend of Fig. 3 are used in conformity with the definitions of Kear and Schofield (1959).

### PALEONTOLOGY AND DISCUSSION

Fossil occurrences within the Hetherington Inlier (Fig. 3) and others nearby (Fig. 2) that are relevant to the present discussion are presented, as Table 1.

Of particular interest in the Hetherington Inlier is the fact that small ( $\frac{1}{4}$  in. in length) specimens of *P. marshalli* have been collected from siltstones (N55/f608) 100 ft below the conglomerate containing *T. bensoni*

(N55/f536). The latter fossil, which hitherto has been considered to be restricted to the Otapirian Stage (Marwick, 1953; Fleming, 1953, 1957), is thus shown to range up into the Ururoan (Marwick, 1953) in South Auckland (provided that the base of that stage be recognised at the lowest occurrence of *P. marshalli*; cf. Campbell's 1955, 1956 general usage for stage boundaries; and Speden and McKellar's, 1958, pp. 651-2, usage for the Ururoan at the incoming of small specimens of *P. marshalli*).

In the Hetherington Inlier, 650 ft of poorly-exposed unfossiliferous beds are present below the small *P. marshalli*. The same fossil is also known from the Rotowaro - Glen Afton road (N56/f641), again below normal sized specimens (N56/f642), and with only unfossiliferous beds below. It has also been identified, with less certainty, by Dr J. Marwick (pers. comm.) from poor material, close to the base of the formation, near Wilton No. 2 Mine (N56/f577). However, several lines of admittedly inconclusive evidence suggest that in South Auckland the small specimens of *P. marshalli* may appear within at least the lower part of the range of those of normal size, rather than only below it as at Nugget Point (Speden and McKellar, 1958):

(1) Small specimens of *P. marshalli* are present in the Hetherington Inlier at an estimated 2,650 ft below the base of the overlying sandstone formation; yet near the type section of the Pongawhakatiki Siltstone (Fig. 2) there are 1,500 ft of siltstone with normal-sized *P. marshalli* both in the basal conglomerate (N56/f549) and within 500 ft of the top (N55/f599).

(2) At Te Puroa Road the basal conglomerate with normal-sized fossils (N56/f549) is underlain by sandstones with plant impressions. They have no correlatives in the lowest beds of the Hetherington Inlier, as might be expected if the small-sized *P. marshalli* were normally in basal or near-basal beds.

(3) The three coarse members of the Hetherington Inlier have been traced southwards as coarser horizons within the Pongawhakatiki siltstones. Although the tracing is of uncertain validity, it is supported by the available dips and by the fact that the lithology of the lower part of bed (b) in the type section (say 2,500 ft down from the top of the formation) is similar to that of the bed containing small *P. marshalli* on the Rotowaro - Glen Afton road (N 56/f641).

(4) Along the Rotowaro - Glen Afton road, the small *P. marshalli* (N56/f641) is present in at least two horizons, 200 ft apart. These are underlain by 1,500-2,000 ft of siltstone, and then by sandstone. This latter siltstone at least, and probably some sandstone, would be placed tentatively in the Pongawhakatiki Siltstone formation.

There are, therefore, two main conclusions: firstly, that since *T. bensoni* and *Lopha* cf. *baidringrina* occur above small *P. marshalli* in Hetherington Inlier, both are of Ururoan (lower Jurassic) age there; and secondly, that on the basis of the present admittedly inconclusive evidence, small specimens of *P. marshalli* in the west Auckland area appear to be within at least the lower part of the range of normal-sized specimens, rather than only below it.

TABLE 1.—Fossil Occurrences in the Hetherington Inlier and Nearby

| Fossil Sample No.          | Locality                                                                                                                            | Grid Ref.<br>In N55 (1946 Ed.)<br>Or N56 (1944 Ed.) | <i>P. marsballi</i> (Trech.)<br>(Normal Sized) | <i>P. cf. marsballi</i> (Trech.)<br>(Small Sized) | <i>L. cf. baldingeriana</i><br>(Emmettich) | <i>T. bensoni</i> Marwick | Plant Fragments | Approx. Depth Below<br>Top of Formation (ft) | Remarks                                                                                    |
|----------------------------|-------------------------------------------------------------------------------------------------------------------------------------|-----------------------------------------------------|------------------------------------------------|---------------------------------------------------|--------------------------------------------|---------------------------|-----------------|----------------------------------------------|--------------------------------------------------------------------------------------------|
| (A) In Hetherington Inlier |                                                                                                                                     |                                                     |                                                |                                                   |                                            |                           |                 |                                              |                                                                                            |
| N55/f1                     | Kouratahi Stream, 1½ miles S of<br>Hetherington Rd.                                                                                 | N55/514734                                          | x                                              |                                                   |                                            |                           |                 | c2250                                        | Coll. J. Henderson and<br>L. I. Grange (1926, pp.<br>33-7).                                |
| N55/f500                   | Below Hetherington Rd, Ruawaro,<br>in tributary, ¼ mile E of its<br>junction with Kouratahi Stream.                                 | N55/502758                                          | x                                              |                                                   |                                            |                           |                 | 2200-2350                                    | Coll. J. C. Schofield.                                                                     |
| N55/f536                   | As for N55/f500, but 30 ch E of<br>junction; from weathering-out<br>conglomerate boulders beside Mr<br>Smith's farm track crossing. | N55/503758                                          |                                                |                                                   | x                                          | x                         | x               | 2500-2550                                    | Coll. C. F. Hunt, R. F.<br>Thorburn, I. G. Drury,<br>J. C. Schofield (Flem-<br>ing, 1953). |
| N55/f608                   | As N55/f500, but 35 ch E of junc-<br>tion.                                                                                          | N55/505758                                          | x                                              |                                                   |                                            |                           |                 | 2650                                         |                                                                                            |

| (B) Other Significant Localities |                                                                                        |            |   |        |
|----------------------------------|----------------------------------------------------------------------------------------|------------|---|--------|
| N55/f599                         | 15 ch SSW of Trig. Pongawhakatiki.                                                     | N55/545593 | x | 500    |
| N56/f549                         | Te Puroa Rd. 164 ch W of Trig. R. and 3 ch W of western boundary fault of Wilton Mine. | N56/571557 | x | 5500   |
| N56/f577                         | 36 ch at 006° from Wilton No. 2 Mine mouth.                                            | N56/569595 | ? | c5500  |
| N56/f641                         | Rotowaro - Glen Afton road cutting, 12 ch NE of turn-off to Pukemiro Station.          | N56/572695 | x | c3000? |
| N56/f642                         | As N56/f641, but 10 ch W of turnoff.                                                   | N56/567692 | x | c2000? |

Determination J. Marwick (pers. comm.).  
Same fossil also occurs 200 ft lower.

Collectors other than the author are noted by "Coll". Published determinations are indicated by reference.

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## APPENDIX

An occurrence of *Torastarte bensoni* Marwick with *Pseudaucella marshalli* (Trechmann) in the Hokonui Hills, Southland.

By I. G. SPEDEN, New Zealand Geological Survey, Lower Hutt.

Additional support for the Ururoan age of the Hetherington Inlier occurrence (N55/536, GS 5728) of *Torastarte bensoni* Marwick and *Lopha* cf. *haidingeriana* (Emmrich) is given by the occurrence of specimens of *T. bensoni* with normal-sized *Pseudaucella marshalli* (Trechmann) in a coarse grey conglomerate grit on the crest of Heale Ridge, west side of Otapiri Stream, S169/788, GS 7264.

From this locality on 1 October 1953, Mr I. C. McKellar, New Zealand Geological Survey, collected 10 internal moulds of *P. marshalli*; the largest being 24 mm (c. 1 in.) in length, the smallest 19 mm (c.  $\frac{3}{4}$  in.). Closely associated with the randomly oriented valves of *P. marshalli* are a left and a right valve of *T. bensoni*. The right valve matches the holotype (a right valve) described by Marwick (1953), but differs from the right valve of the specimen from Hetherington Inlier (N55/536, 5728) described by Fleming (1957) in that the ventral edge of the escutcheon is less encroaching and does not form such a distinct, tooth-like nymph.

The occurrence of *T. bensoni* in conglomeratic grit at all four known localities is perhaps indicative of a preferred facies.